Final degree Thesis

Grau en Enginyeria en Tecnologies Industrials (GETI)

Solar Photovoltaic Installation in Lys School

Report

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Abstract

Nowadays, renewable energies are widely spread around the world. The urge to find alternatives to the conventional ways of creating energy is more than obvious. In particular, Spain is one of the most appropriate countries in Europe for solar energy on account of the solar irradiation that receives.

Facilities such as schools, commercial business, industries, offices, etc. that consume energy during the daylight are the perfect target for using solar energy. This is exactly the aim of this project: the design of a photovoltaic installation in a school. The school is “Escola Lys”, near the centre of Barcelona, a small and familiar school that tries implement different activities that respect the environment. This is why a commission for environmental projects was created, it includes different sections to carry out projects, from solutions for waste and recycling to energy measures.

The intention is to obtain energy from a clean source following the aim of the school to become a “Green School”. To implement this measure, it is needed to obtain information of the electrical needs, the available space for placing the panels and the measures of the near buildings. Thanks to the administration of the school it was possible to obtain enough information to do the bases of a future project. This thesis is thought to be studied an improved for another student in the near future and turn the project into reality.

In the first place, a study of the parameters of the school has been done: analysing the electrical needs, and therefore the peak capacity that should be installed. After this, two possible location for the panels were presented, the PV array will be conditioned by the emplacement and therefore it will be studied a particular installation for each case.

Finally, a simulation for both options has been carried out with PVsyst. This software allows to calculate the energy that would be generated taking into account the losses that the installation will suffer, among many other things. The results of these simulations will determine the best emplacement for the PV generator. Also, the project has been complemented with an economic study and the evaluation of the environmental impact.

Contents

List of figures

List of tables

List of graphs

1. Glossary

PNIEC: Plan Nacional Integrado de Energía y Clima

IDAE: Instituto para la Diversificación y Ahorro de la Energía

DC: Direct Current

AC: Alternating Current

RMS: Root Mean Square

ITC-BT: Instrucciones Técnicas Complementarias – Baja Tensión

PSH: Peak Sun Hours

PR: Performance Ratio

IVPEE: Impuesto sobre el Valor de la Producción de Energía Eléctrica

MPP: Maximum Power Point

UNE: Una Norma Española

REBT: Reglamento Electrotécnico de Baja Tensión

XLPE: Polietileno Reticulado

STC: Standard Test Conditions

NOCT: Normal Operating Cell Temperature

EVA: Ethylene Vinyl Acetate

2. Preface

2.1. Motivation

I have been interested in renewable energies since I started studying Industrial Engineering, I think that global warming is an issue that should make people change its way of thinking and modify bad habits. This is the reason why I wanted to focus my project in renewable energies in the first place, to implement engineering projects that can be respectful with the environment.

The opportunity to design a PV installation for a school in Barcelona was proposed to me by Oriol, the director of this project, although it wasn't the first idea that I had for my thesis, the idea of helping to develop a PV array that would possibly become a real installation in the near future convinced me.

2.2. Renewable and Solar Energy

Nowadays, with the evolution that the planet is suffering it is really important to seek and improve the alternatives of fossil fuels; which are petroleum, coal and natural gas. These fuels are classified as non-renewable resources because the reserves are being depleted much faster than they are being replaced by the natural resources.

Therefore, renewable energy is becoming more important and the improvement of this kind of energy is a primary concern at this time. Renewable energy can be obtained from sunlight, wind, different kinds of hydro resources (rain, tides, waves) and geothermal heat.

In the following figure, we can see the evolution of renewable power capacity from 2007 to 2017.

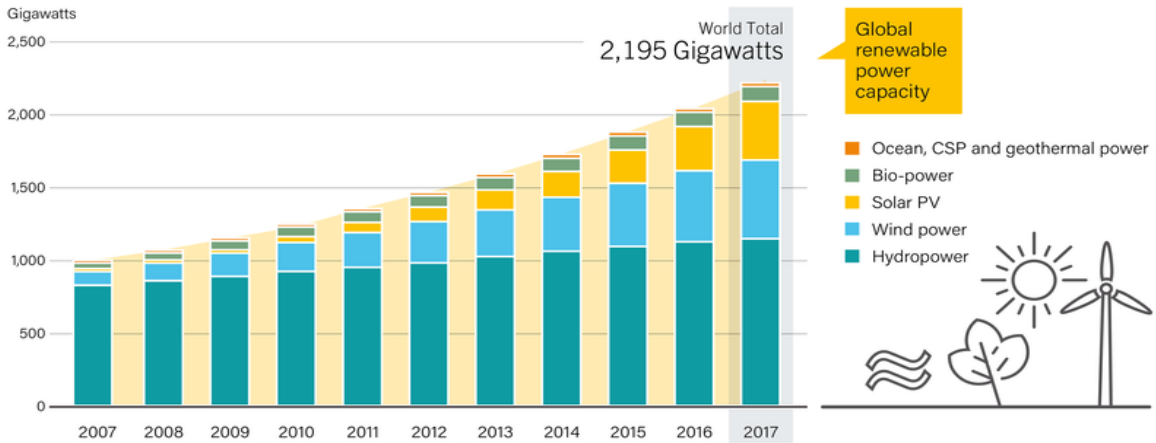


Figure 2.1. Global Renewable Power Capacity from 2007 - 2017 ([1], 2017)

If we focus on solar energy, many statistics prove that this clean technology is the one that has grown the most in the past years. This has been possible, among other reasons, because of the reduction of its cost, government facilities and the evolution of the technology.

We can see another bar chart particularised to photovoltaic energy:

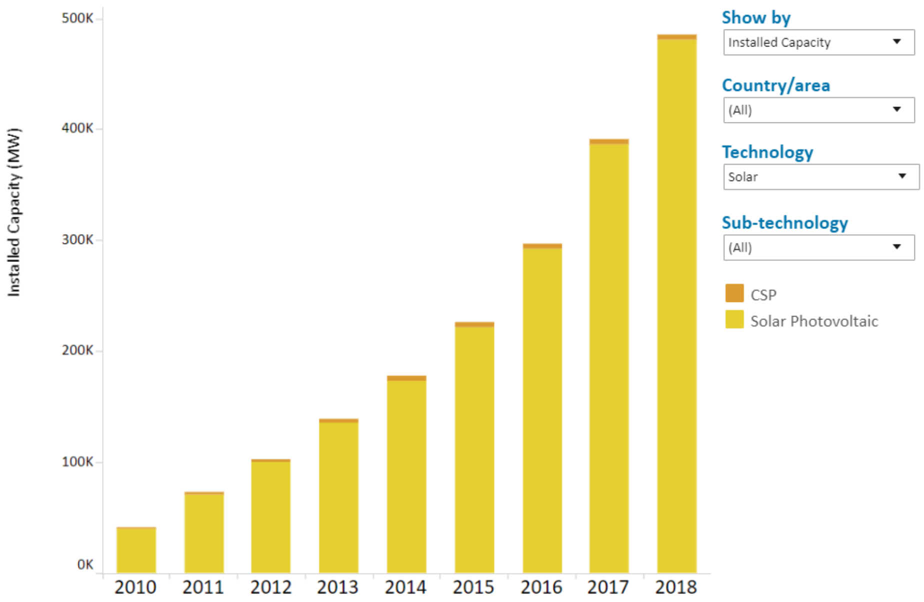


Figure 2.2. Installed Capacity Trends ([1], 2017)

Moreover, it is important to take into account the distribution of solar radiation on the surface of the planet. In an attempt of simplifying the recollect of data, the amount of solar irradiation on a global scale can be represented from the horizontal global solar irradiation.

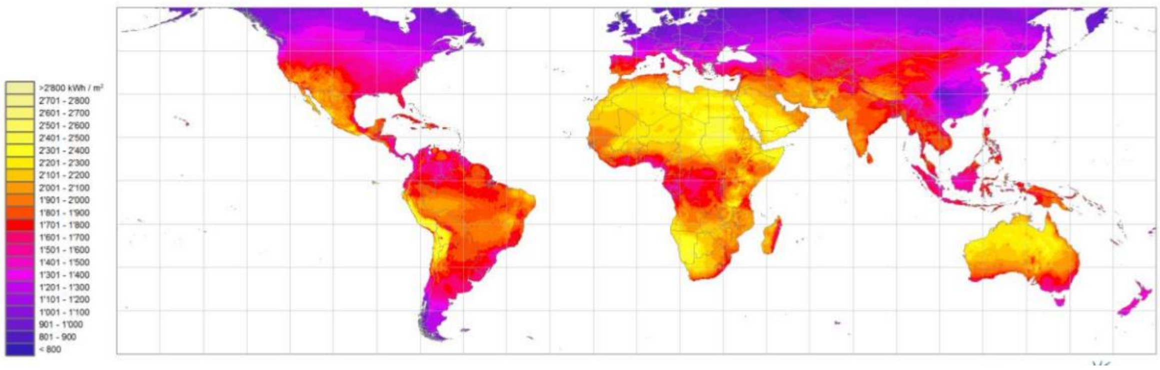


Figure 2.3. Map of yearly sum of global irradiation in kWh/m2 (period from 1991 to 2010) ([9])

2.3. Solar and Renewable Energy in Spain

The solar resource is abundant in Spain, since it has very good conditions suitable for photovoltaic solar energy, with areas of high irradiance. The situation compared to other European countries is comparatively very favourable.

The main feature of this resource is to be available throughout the surface at the same time, however being conditioned by the shadows of both natural and artificial elements and by the particular climatic conditions of each geographical area.

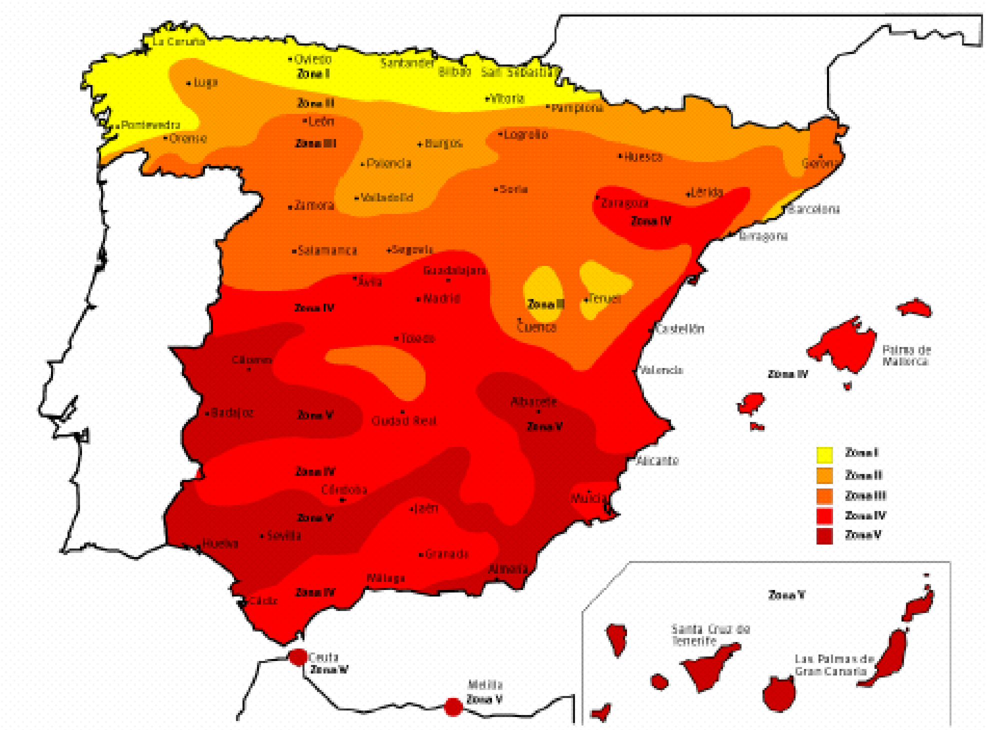


Figure 2.4. Solar Irradiance in Spain ([2], 2019)

The National Integrated Energy and Climate Plan (PNIEC) 2021-2030: defines the objectives of reducing greenhouse gas emissions, penetration of renewable energies and energy efficiency. It determines the lines of action and the path that, according to the models used, is the most adequate and efficient, maximizing the opportunities and benefits for the economy, employment, health and the environment; minimizing costs and respecting the needs of adaptation to the most CO_2 intensive sectors.

The objective set is to achieve the PNIEC reduced emissions by the year 2030, this reduction must be at the least 20% compared to 1990. The measures in the Plan allow to achieve a reduction in emissions of greenhouse gases of the 21%.

The National Integrated Energy and Climate Plan provides for the year 2030 a total installed power in the electricity sector of 157 GW, of which 50 GW will be wind power; **37 GW photovoltaic solar**; 27 GW combined gas cycles; 16 GW hydraulic; 8 GW pumping; 7 GW thermoelectric solar; and 3 nuclear GW, as well as smaller amounts of other technologies.

An important part of the economic impacts contemplated in this study derives from the investments associated with the development of the policies and measures associated with the Plan. It is estimated that total investments to achieve the objectives of the PNIEC will reach 236.1241 million of euros (€ M) between 2021-2030. These investments can be grouped by measures and distributed as follows: savings and efficiency: 37%, renewable: 42%, networks and electrification: 18% and the rest measures: 3%.

The PNIEC generates a net increase in employment between 250.000 and 364.000 people per year (a 1.7% increase in employment in 2030). The unemployment rate would be reduced, compared to the Tendency scenario, between 1.1% and 1.6%. Investments in renewables would generate between 102.000 and 182.000 jobs/year.

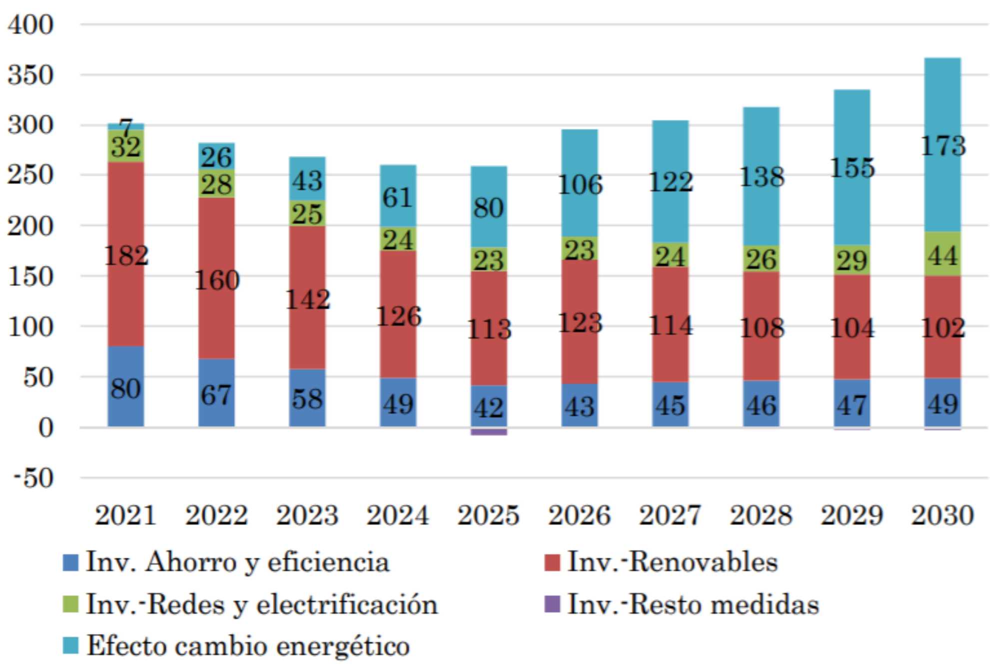


Figure 2.5. Impact on employment by type of measure (thousand people/year) ([2], 2019)

3. Introduction

3.1. Objectives

The main objective of this project is to elaborate the design and installation of a possible photovoltaic system for Lys School in Barcelona.

This project is thought to be continued and improved in the near future by another student in order to complete all the points that might have only been studied briefly. It is important to mention that this school is involved in an Ecological Commission, where other students from "Universitat Autonoma de Barcelona" are working and doing their own thesis. Since these students start their thesis once I finish mine, this project is also thought to be used as a base for implementing an Energy study for this commission.

It will be important to study the site where the photovoltaic array should be installed in order to reduce the impact of shadows from other buildings as much as possible and obtain the maximum profit of the installation. Also, a research of the different options that exist in the market should be done to choose the best relation quality-price for the components.

Moreover, it is important to understand how photovoltaic energy works and all the components that are included in a photovoltaic system.

Finally, it should also be taken into consideration the environmental impact of the installation and do it with a reasonable budget, since this installation needs not only to be sustainable but to be viable for the school.

3.2. Scope of the project

As mentioned in the previous part, this project is focused on developing the design of a possible photovoltaic system in a school, concretely "Escola Lys" that would be installed in the near future.

Thanks to the documentation provided by the school, maps of the different floors (including the playground where the PV arrays will be installed), electricity bills, hourly consumption, etc., it was possible to recreate a real case. That is the reason why this project tries to be the bases for a future development in the school that will imply a reduce in costs and a sustainability solution that fits the goal of being a "Green School".

It is also important to point out that this project also helps new generations to grow up in a more respectful environment and learn about renewable energy.

4. Literature Review

4.1. PV Systems

Photovoltaic systems have reduced its price considerably in the recent years, allowing many people to take advantage of this clean way of producing energy. Moreover, it has a simple installation, which makes it the perfect system for many applications. Also, the working hours of the school coincide with the hours of more generation.

PV systems are formed by different elements that allow their operation, such as photovoltaic solar panels that absorb solar irradiation; the inverters for the transformation of DC current to AC current and habitually the batteries to store the energy.

The principal components will be explained with more detail below.

4.1.1. Solar Cell

The solar cell is the component responsible of absorbing the sunlight and converting it into electrical energy through the photovoltaic effect. The solar cells are made of a semiconducting material, which in most cases is silicon.

Generally, in a semiconductor when energy light is absorbed (photon) they release electrons creating a hole. These electrons usually fill quickly another hole and the energy provided by the photon is dissipated.

In a solar cell, the key for generating useful power is to channel the free electrons through an external resistance before they recombine with the holes. This is achieved with the help of the p-n junction. As free electrons are generated in the n layer by the action of photons, they can either pass through an external circuit, recombine with positive holes in the lateral direction or move toward the p layer. If the n layer is made extremely thin, the movement of the electrons and, therefore, the probability of recombination within the n layer is greatly reduced. This will create a difference in electric potential and therefore a voltage between the two parts of the material. ([3], 2015)

When these solar cells are arranged, they form a PV module. Finally, to achieve the desired energy generation, modules are wired in series and parallel to form a PV array.

There are different types of panels:

- Monocrystalline: composed of a single pure silicon crystal.
- Polycrystalline: composed of multiple silicon crystals.
- Particle solar cell or thin layer: they integrate a photovoltaic substance inside a surface in the form of a crystal.

In the following table, the three types will be compared:

MONOCRYSTALLINE	
High efficiency: 14-17% Spatial efficiency: they need a small surface Long lifetime: up to 30 years In bad solar conditions, better results than the other types (the electrons flow easily)	More expensive (about 3,2 to 3,5 €/W) If they are covered, the whole system is affected since there is only one crystal
POLYCRYSTALLINE	
Simple way of construction, therefore they are cheaper (2,8 to 3,3 €/W) Less affected to the heat, the intern resistance is better	Less efficiency: 12-14% Less spatial efficiency: they need a greater surface Less lifetime, even though still good: up to 25 years
THIN LAYER	
Cheapest option (about 1,5 to 2,2 €/W) They have certain flexibility Good resistance to environmental factors	They need a big surface to absorb the irradiation Low efficiency: 7-12% Low lifetime: maximum 12 years

Table 4.1. Comparison between different types of solar panels

Nowadays, the most used panels are the polycrystalline. Although this type has more disadvantages, the efficiency is quite similar, and its price is more competitive.

4.1.2. Inverter

The inverter is the responsible for power conditioning and control system. In a grid-connected PV system, direct current (DC) needs to be transformed into alternating current (AC) suitable for injecting into an electrical power grid (in monophasic, normally 230 V RMS at 50 Hz).

The inverter is an essential part of the PV system, and therefore it is important to choose it carefully. The efficiency of the inverters should be more than 95%. This value depends on the variation of the power of the installation, due to this, it is important that the inverter tries to work with nearby powers or equal to the nominal, since if the input power to the inverter from the PV panels vary, performance decreases.

To prevent the performance from decreasing with the variation in the power of input from solar panels, inverters must be equipped with electronic devices that track the maximum point power of the panels, allowing to obtain the maximum possible efficiency of the photovoltaic generator in any operating circumstance.

4.1.3. Energy Storage

Conventionally, PV systems use batteries in order to store energy for using it when there is no solar irradiation; for example, at night or when the sky is clouded. These batteries convert the electrical energy into chemical energy in order to be stored, and once it is needed, it is converted to electrical energy again.

The objective of this project is to dimension the PV array for the auto consumption, since the hours that the school is open coincide with the hours of more solar irradiation. Nevertheless, during the weekend there will be for sure surpluses or even at some hours the production could be greater than the consumption.

Despite this, for a small installation, the implementation of batteries implies a big additional cost, and if the installation is not isolated, it is better to buy the electricity from the grid and sell the surpluses. Therefore, this project won’t implement batteries.

4.2. Principal electrical parameters

It is essential to know the basic electrical parameters of the solar panels:

- Short circuit current (I_{SC}): is the maximum current generated in the panel when no load is connected and its terminals are short-circuited.

- Open circuit voltage (V_{OC}): is the maximum voltage provided by the panel when no load is connected between the terminals of the panel and said terminals are on the air.
- Maximum power point (I_{mpp}, V_{mpp}): is the point at which the power delivered is maximum, obtaining the highest possible performance of the panel.

- Form factor (FF): It is the ratio between the maximum power that the panel can deliver and the product of the maximum power current (I_{mpp}) and the maximum power voltage (V_{mpp}). This parameter is used to know the curve I-V feature of the panels.

- Efficiency or performance (η): is the ratio between the maximum power that the panel can deliver and incident solar radiation power. Depending of the technology used when manufacturing the panel can reach up to 18%.

All these fundamental parameters are provided by the manufacturers in the characteristic sheets of the photovoltaic panels. It should be noted that these parameters are not constant since manufacturers take as reference some standard operating conditions which are certain irradiance and temperature conditions determined in the solar cell, these conditions are:

- Irradiance: 1.000 W/m^2
- Spectral distribution: AM 1,5G
- Cell temperature: 25ºC

Usually, the fabricants also include the I-V curve for different irradiance (with a constant temperature of 25ºC) and with temperature variation (with the irradiance under standard measurement conditions, 1.000 W/m^2)

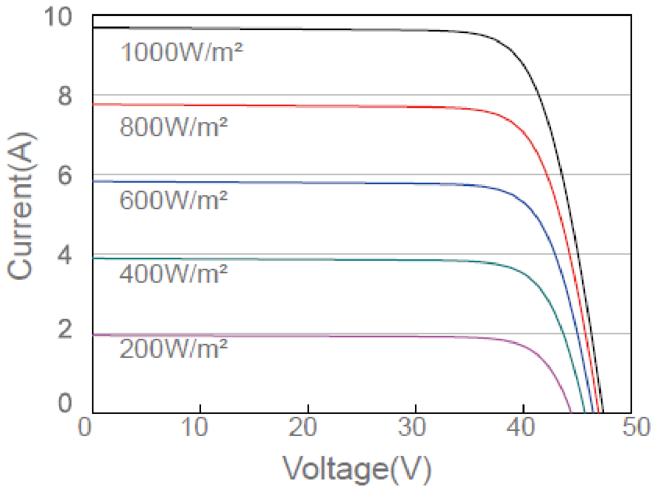


Figure 4.1. Current-Voltage curves at different temperatures of JAP72S01-325/SC (at 1.000 W/m^2)

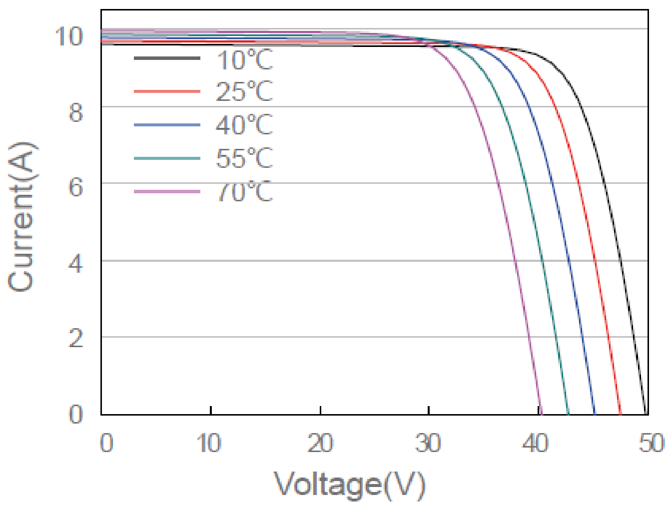


Figure 4.2. Current-Voltage curves at different irradiances of JAP72S01-325/SC (at 25ºC)

5. Case study

5.1. Site details

The school “Escola Lys” is situated in Barcelona, specifically in Street ‘Puig-Reig’, 9, 08006. It is near the centre of Barcelona, reason why it has several buildings around. This will be an important factor to consider for the possible shadows that these buildings would cause.

In the following figure, obtained from the Satellite from Google Maps, we can see the building:

Figure 5.1. Satellite image of Escola Lys ([4], 2019)

The panels can’t be placed in the roof of the building for internal reasons with the community; therefore, one possible location is in the playground. Since it is a small space it would be necessary to implement a photovoltaic pergola or even it could be studied to place them in the wall of the building.

We can see some pictures of the playground; the pergola would be placed in the end of the playground (next to the yellow wall) and it could also be used to proportionate some shadow to the playground for the kids.

Figure 5.2. Pictures of the playground of Escola Lys

Also, with the help of “Sede Electrónica del Catastro” it is possible to obtain the drawing of the building. The part outlined in yellow corresponds to the playground.

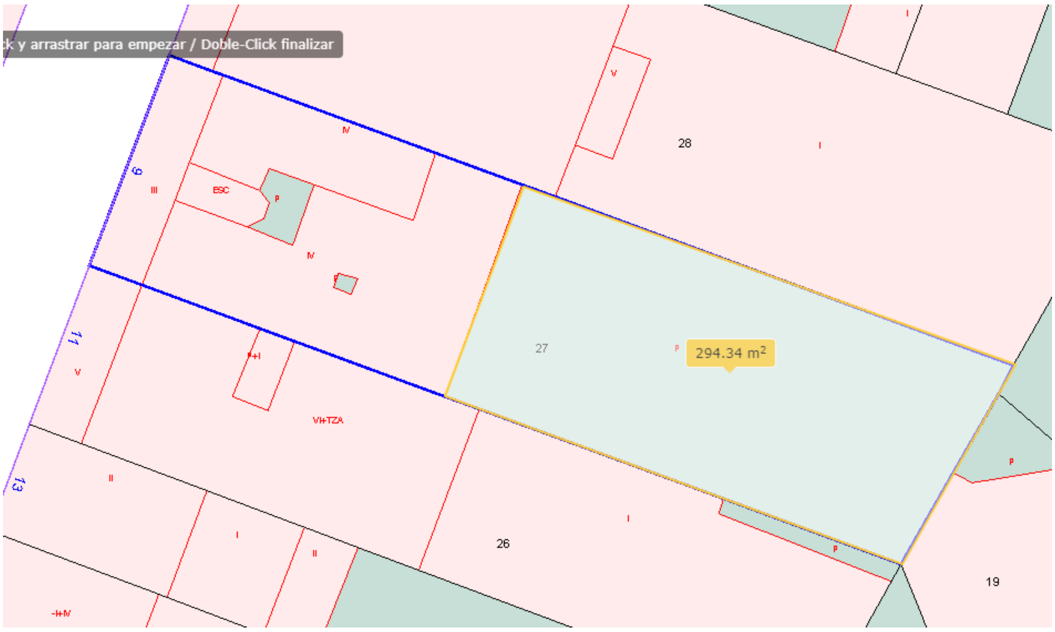


Figure 5.3. Picture from plan view of Escola Lys ([5], 2019)

There is another building for the nursery school and the playground is bigger, therefore it was also proposed to install the panels there. Following the same idea, the intention is to place them with a photovoltaic pergola.

We can see the picture from Google Maps:

Figure 5.4. Satellite image of Petit Lys ([4], 2019)

In this playground, the photovoltaic pergola is thought to be placed in the left part. Currently that space is used to store things of the children such as baby carriages, bags, etc., to keep them in the shadow. That's why the PV pergola not only would help to reduce electrical consumption but will also be useful to keep with this function of creating shadow to keep things under the installation.

Here we can see some pictures of the playground of Petit Lys:

Figure 5.5. Pictures of the playground of Petit Lys

And, the drawing of the building, where again the part outlined in yellow is the playground:

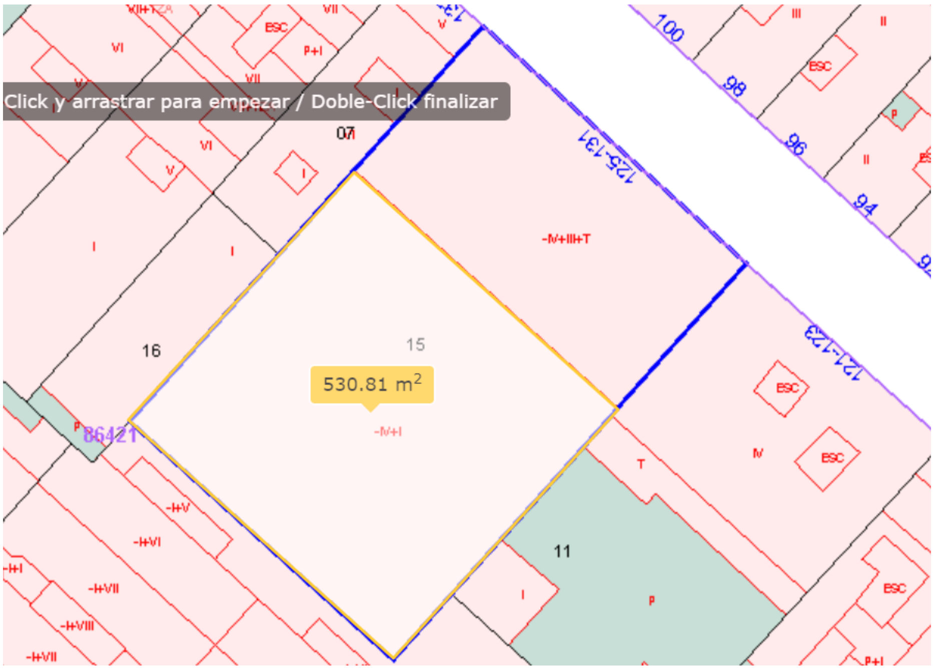


Figure 5.6. Picture from plan view of Petit Lys ([5], 2019)

In the first building, Escola Lys, there are courses from pre-school to 6th grade of school. Whilst on the second building, Petit Lys, there are only the courses of the nursery school.

5.2. Study of the electric needs

To get more introduced in this particular case, it is important to know the consumption and the demand profile. This information will be helpful to decide how many kWp are the appropriate for the installation and do a future analysis of which part of the electricity generated will be auto-consumed.

The school provided the electricity bills from the different meter boxes, in total there are four different electricity contracts. These bills are divided in the following way:

1. Consumption of the basement and the ground floor of Escola Lys
2. Consumption of the 1st and 2nd floor of Escola Lys
3. Consumption of the kitchen of Escola Lys
4. Consumption of Petit Lys

The first bill is contracted with the company “holaluz” and the other three are contracted with “Endesa”. The bills from the first and second floor and the kitchen, provide the consumption for the whole year, whereas, the ones from the ground floor, the basement and the nursery school, only give the information of the last month.

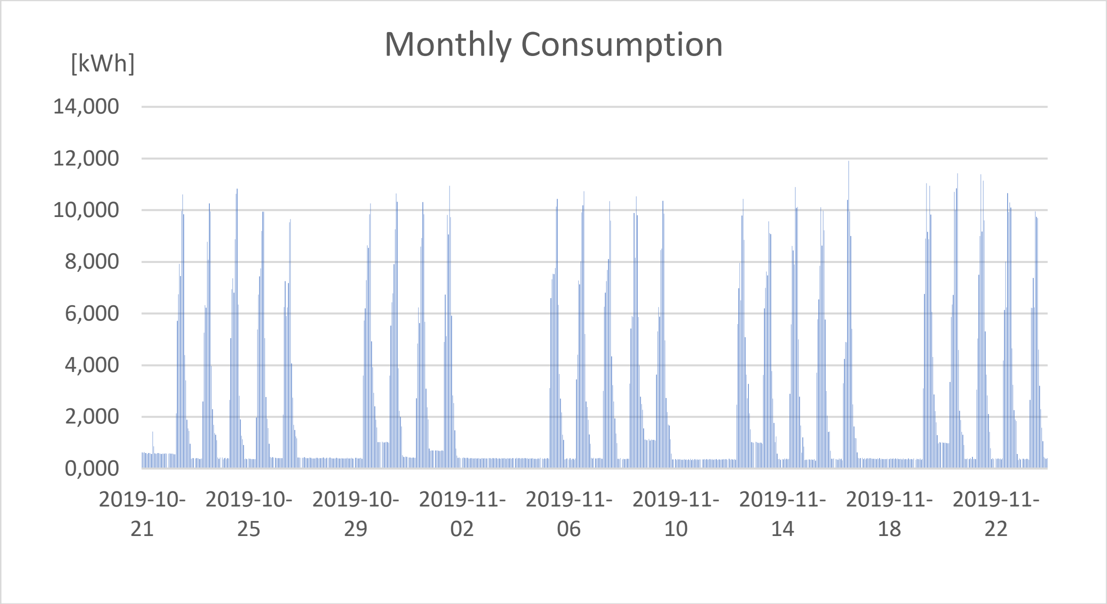
The yearly consumption of the kitchen and the first and second floor sum up 10.093 kWh. For the rest of the bills, the current value was used to calculate an estimated consumption for the year. It can be considered that those parts will consume 7.700 kWh per year. Then the total consumption of the school will be 18.000 kWh per year approximately.

From the bills that are contracted with “Endesa” it was possible to obtain the hourly consumption of the last month. There only was missing the hourly consumption of the bill from the basement and the ground floor.

To include these values, the total consumption of the last period for the basement and ground floor (770 kWh) was multiplied by the percentage of consumption for each hour in the last month obtained from the other three bills. Once this approximation was done, all the hourly consumptions from the different meter boxes were sum up.

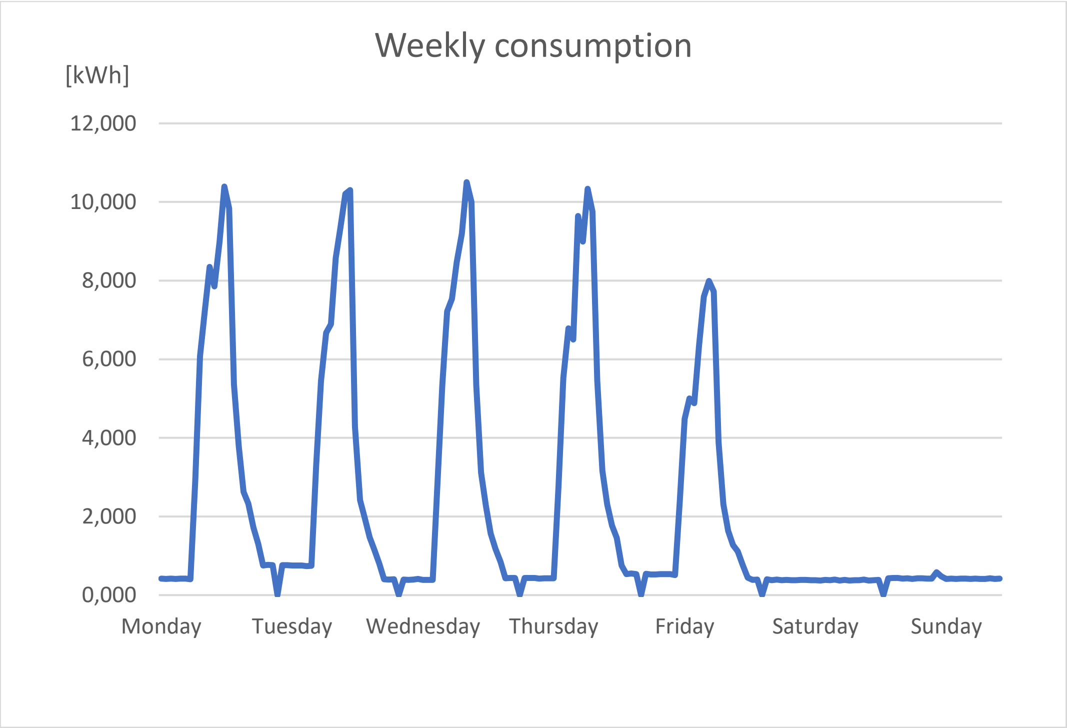
From this total consumption it was posible to obtain the graph for the demand profile for the whole month. Finally these values were classified, and the average values for the consumption of a week and for the consumption of a day were generated.

In the following graphs we can see the results:

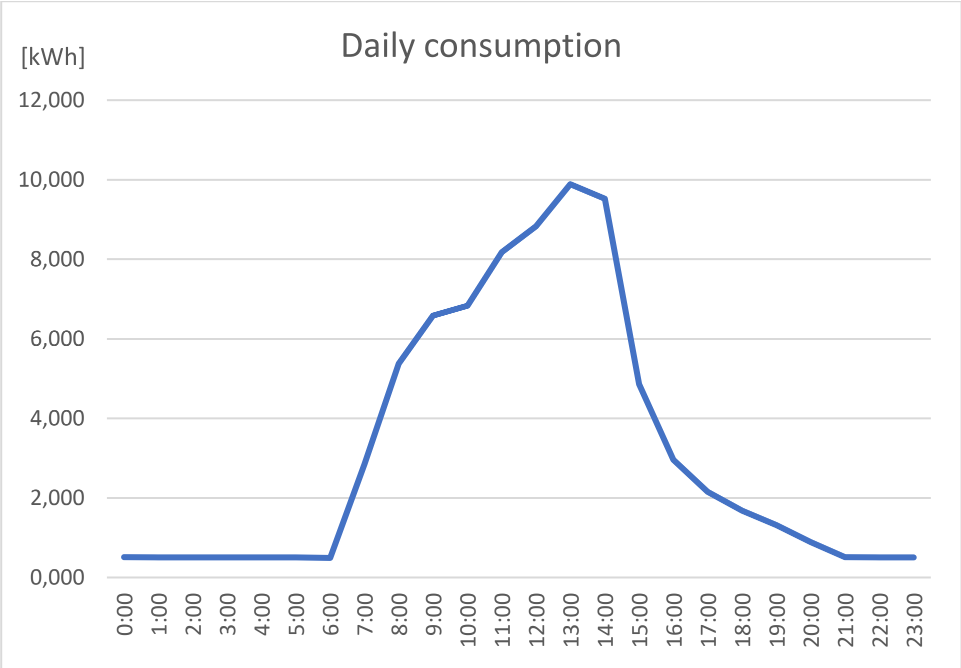


Graph 5.1. Monthly consumption (October - November)

It can be seen that during the whole month, the pattern of consumption is repeated.



Graph 5.2. Average Weekly Consumption (October - November)



Graph 5.3. Average Daily Consumption (October – November)

In the graph 5.2 it is even clearer the difference between the weekdays and the weekends. Also, it can be noticed that there is less consumption on Fridays.

Finally, in the graph 5.3 the demand profile for the weekdays can be observed. The consumption reaches its highest point between 13:00 h and 15:00 h, which match with the cooking hours. Also, the values are high between 9:00 h and 10:00 h, that coincide with the hour that the kids enter to the school. This demand profile suits very well the production of a PV installation.

5.3. Type of self-consumption installation

Depending on the type of installation, the modality of self-consumption, the type of connection (if it is individual or collective) it is needed to do a different administrative processing as it is written by the IDAE ([2], 2019). Therefore, it is important to define which type is chosen in our project.

The different types of self-consumption that exist are described above:

- **Self-consumption without surpluses:** These are self-consumption installations that, although they are connected in the internal network of the consumer that links to the distribution or transport network, does not surplus at any time power to the network. They must be provided with an anti-spill system in accordance with ITC-BT-40.

- **Self-consumption with surpluses:** These are self-consumption facilities connected to the distribution or transport network, which can give power to the network.

    a) Facilities with surpluses with compensation: This mechanism can be applied if the installation has a power smaller than 100 kW and if the source is a renewable one.
    The energy from the self-consumption installation that is not consumed instantly or stored by the associated consumers is injected into the net; when consumers need more energy than the installation of self-consumption, they will buy the power from the grid at the price stipulated in their supply contract (PVPC or free market agreed with the marketer). At the end of the billing period (which may not be longer than one month) the compensation is made between the cost of the energy purchased from the network and the value of the surplus energy injected into the network (valued at the average market hourly price minus the cost of diversions or at the agreed price between the parties, depending on the supply contract to PVPC or free market respectively).

    b) Facilities with surpluses without compensation: In cases where the consumer does not wish to adhere to the compensation mechanism of surpluses, the installation is not met it will dump the surpluses of energy that is not self-consumed instantly or stored.
    This surplus energy will be sold in the electricity market and will receive the same treatment as the rest of the energy produced by renewable sources, cogeneration and waste, it needs to be applied the Tax on the Value of Electric Power Production (IVPEE) of 7% and the toll of generation of 0,5 €/MWh.

All these ways of self-consumption can be individual or collective with several consumers. In both cases the installation proposed will be self-consumption with surpluses. The ideal situation would be to implement compensation. Nevertheless, this is quite a new regulation and the prices of the compensation haven't been stablished. Once the project is done it will certainly can be done the compensation because the installation has less than 100 kW installed and it comes from a renewable source; but, for this thesis and for the calculations related with the economic study, the installation will be without compensation.

Also, it is needed to implement a collective consumption since there are two buildings. To implement a collective consumption for nearby facilities through network., one of the following requisites must be accomplished:

1) The connection is made to the low voltage network that is derived from the same transformation centre to which the consumer belongs.

2) The connection of both consumption and generation is made in low voltage, and the distance between the generation and consumption meters is less than 500 m, measured in orthogonal projection in the plant.

3) The generating facility and associated consumers are located in the same cadastral reference, taken as such if the first 14 digits coincide (with the exception of the autonomous communities with their own cadastral regulations).

The second condition is fulfilled because the two buildings are closer than 500 m.

5.4. Solar PV System sizing

5.4.1. Solar specifications

We can obtain the solar radiation in the building with the help of PVgis. This website provides, among others, the monthly solar average irradiation of a year, for the horizontal component and for the optimum angle.

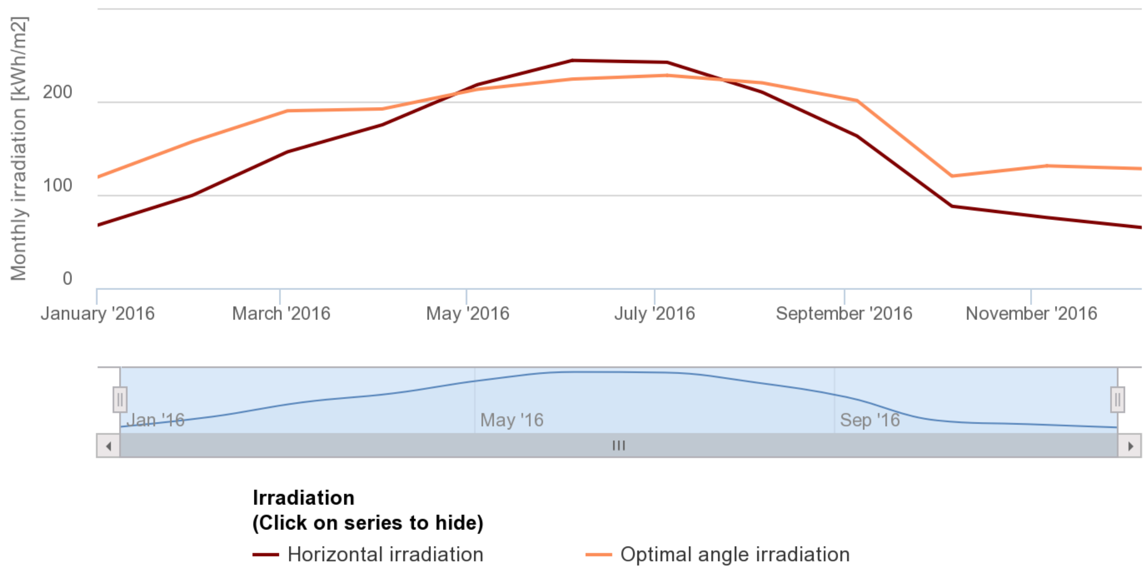


Figure 5.7. Monthly Solar Irradiation in Barcelona ([6], 2019)

It is also possible to obtain the radiation of a certain angle, which will be useful once the inclination and orientation and inclination of the panels is decided.

As mentioned before, an important step is to decide the peak capacity of our system. Peak capacity describes the energy output of a system achieved under full solar radiation and it is expressed in kWp. Despite this, since the installation is really limited by the space, the desired peak capacity will be calculated but the number of panels installed must be adapted to the space.

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Ideally, to decide the desired peak capacity, the system would be designed for the most unfavourable month, which is December. Nevertheless, since there are two bills that don't include the consumption for that month, it will be better to calculate it for the month of November. Also, the values for the irradiance are quite similar for these two months.

With the help of PVgis, it was possible to obtain a graph for the daily irradiance and the corresponding table with the values:

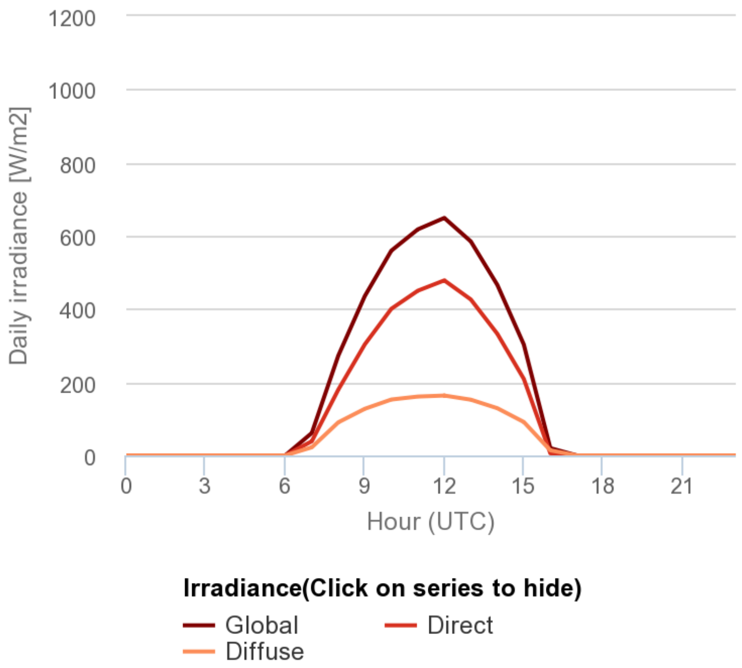


Figure 5.8. Daily irradiance profile for an inclined plane (35º) for November in Barcelona ([6], 2019)

Irradiance on a fixed plane

Time	00:45	01:45	02:45	03:45	04:45	05:45	06:45	07:45	08:45	09:45	10:45	11:45	12:45	13:45	14:45	15:45	16:45	17:45	18:45	19:45	20:45	21:45	22:45	23:45
G(i)	0	0	0	0	0	0	0	61	273	435	559	617	649	584	466	303	20	0	0	0	0	0	0	0
Gb(i)	0	0	0	0	0	0	0	39	180	303	400	450	478	426	332	209	6	0	0	0	0	0	0	0
Gd(i)	0	0	0	0	0	0	0	22	90	127	153	161	163	152	129	91	14	0	0	0	0	0	0	0

G(i): Global irradiance on a fixed plane [W/m2].
Gb(i): Direct irradiance on a fixed plane [W/m2].
Gd(i): Diffuse irradiance on a fixed plane [W/m2].

Table 5.1. Irradiance on a fixed plane (35º) for November in Barcelona ([6], 2019)

The radiation for November is 3,967 kWh/m^2, and the electricity needs for the whole month, obtained from the electricity bills are 2.030 kWh; which implies that the average daily needs are 59,7 kWh (the period from the bills include 34 days).

The next step is to convert this radiation into peak sun hours (PSH). The term "peak sun hours" refers to the solar insolation which a particular location would receive if the sun was shining at its maximum value for a certain number of hours. Since the peak solar radiation is 1 kW/m^2, the number of peak sun hours is numerically identical to the average daily solar insolation. That means that in November we have 3,967 PSH.

To obtain the peak capacity we use the following expression:

$$Peak\ capacity = \frac{\text{Energy requirement}}{\text{PSH} * \text{Performance Ratio}}$$

The Performance Ratio is the factor that considers the losses of the system. The recommended PR for solar installations is 0,8. After substituting the values in the equation:

$$Peak\ capacity = \frac{59{,}7}{3{,}967 * 0{,}8} = 18{,}8\ kWp$$

According to this, the Peak Capacity that should be installed in the school is 18,8 kWp. Nevertheless, as the space the final installed capacity could be less. In the following points the maximum number of panels will be calculated and also a study of which is the most profitable situation.

5.4.2. Angle orientation and inclination

The placement and orientation of solar panels is a really important issue to consider when designing a PV array. This happens because a solar panel will harness the most power when the Sun’s rays hit its surface perpendicularly.

The Azimuth Orientation is the compass angle of the sun as it moves though the sky, in the north hemisphere it goes from East to West over the course of the day. Therefore, the best orientation to face the panels in the north hemisphere is to the south.

To measure this angle, usually the south is taken as a reference which means that it is angle 0º (West equals to +90º and East to -90º).

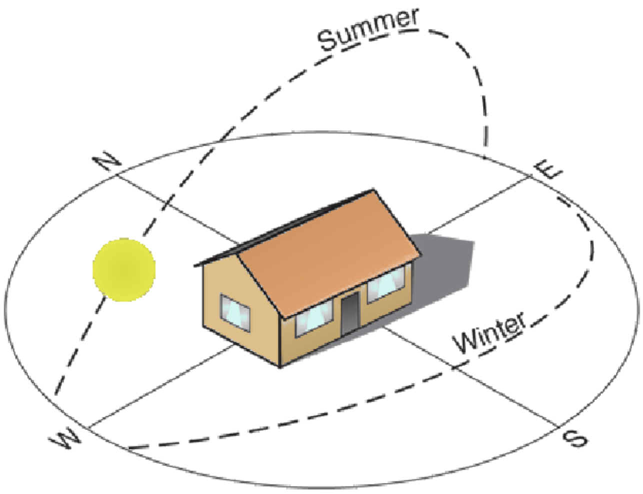


Figure 5.9. Representation of the Sun Path in the north hemisphere ([8], 2019)

In the future installation, the azimuth angle will be determined by the characteristics of the space. In the first possible location, **the "Escola Lys", the panels would be placed parallel to the wall of the playground that it is opposite to the school, therefore the azimuth angle for the installation in Escola Lys would be -69º.**

Figure 5.10. Possible location for the Solar Panels in Escola Lys ([4], 2019)

In the other possible location, the "Petit Lys", the panels will be parallel to the left wall of the playground, as shown in the next figure, the azimuth angle will be -48º.

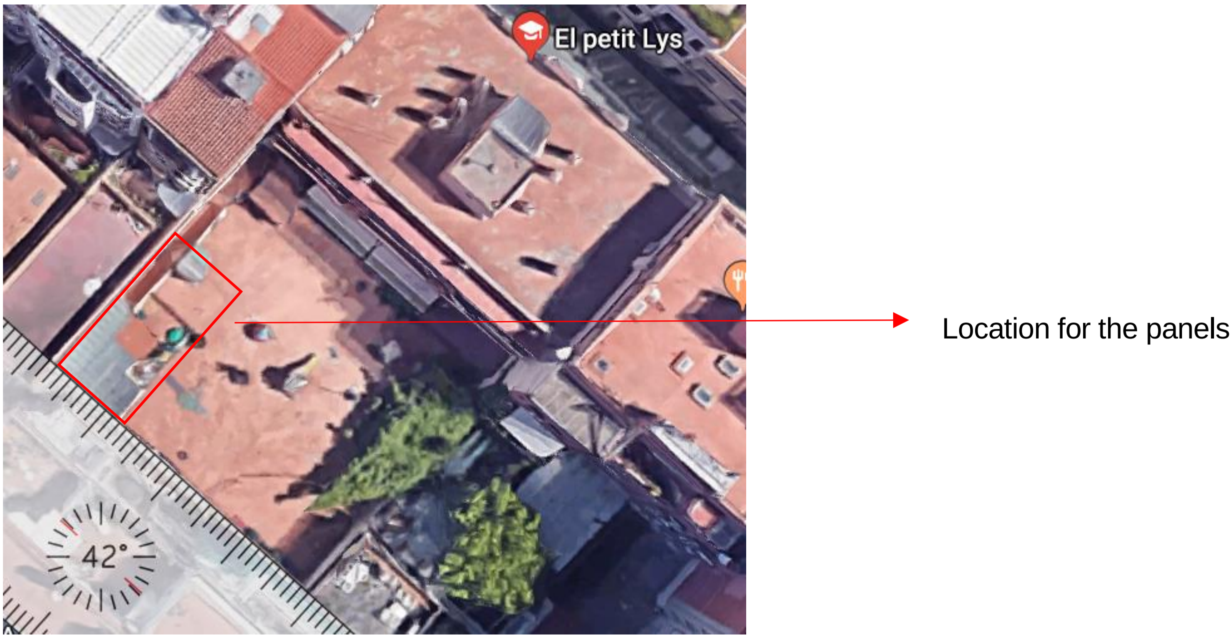


Figure 5.11. Possible location for the Solar Panels in Petit Lys ([4], 2019)

The inclination also needs to be considered; this angle is called the Tilt angle. The inclination of the sun, called the zenith angle, varies through the day and reaches its maximum elevation around midday.

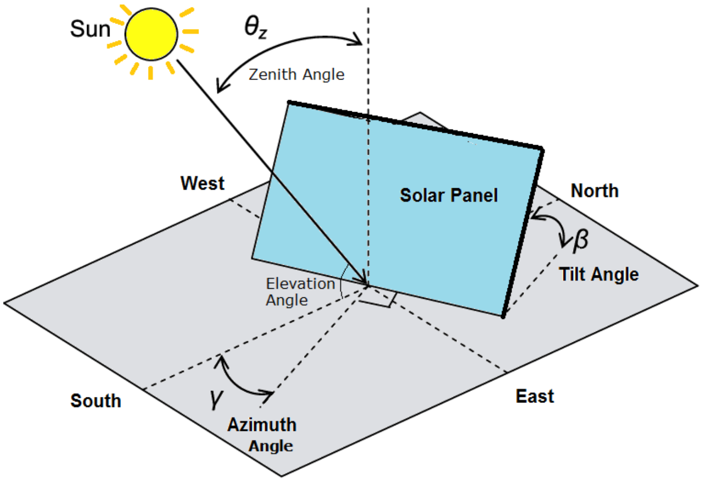


Figure 5.12. Representation of the different angles of a Solar Panel ([7], 2019)

The tilt inclination in solar installations usually varies depending on the type of installation (grid-connected or stand-alone) and if the electricity needs vary through the year. In most cases, grid-connected installations tend to maximize the irradiation through the whole year and stand-alone installations tend to calculate the tilt angle for the most unfavourable month (usually December). Despite being grid-connected, is better to design this installation for the winter, because during July and August the electricity demand is almost null.

To decide the optimal tilt inclination, the programme PVsyst was used. This programme gives a graph of the Transposition Factor as a function of the plane tilt and azimuth. These graphs also indicate the actual choice by a violet dot on the curves, showing at once where you are positioned with respect to the optimum.

For Escola Lys, the optimal tilt inclination was 30º, whilst for Petit Lys the optimal inclination is 45º approximately.

In the following figures we can see the graph mentioned before for each case:

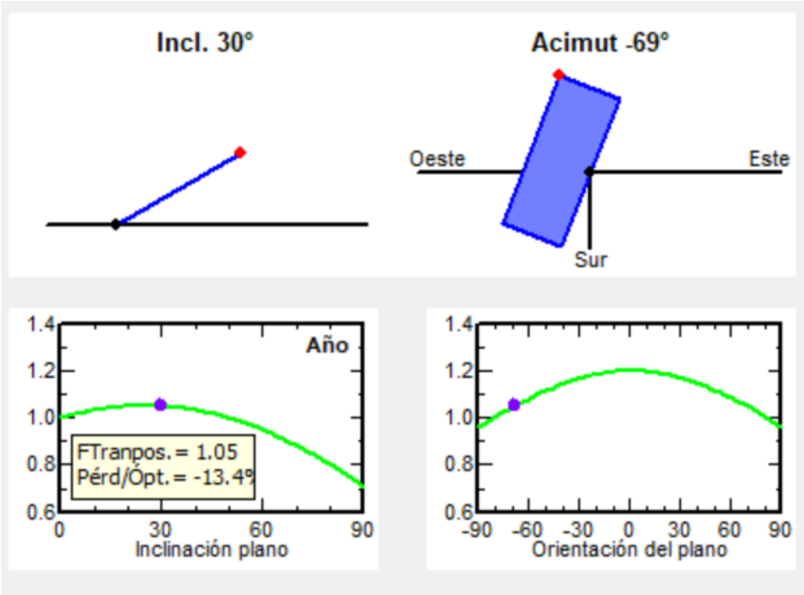


Figure 5.13. Optimal inclination and orientation for Escola Lys ([9])

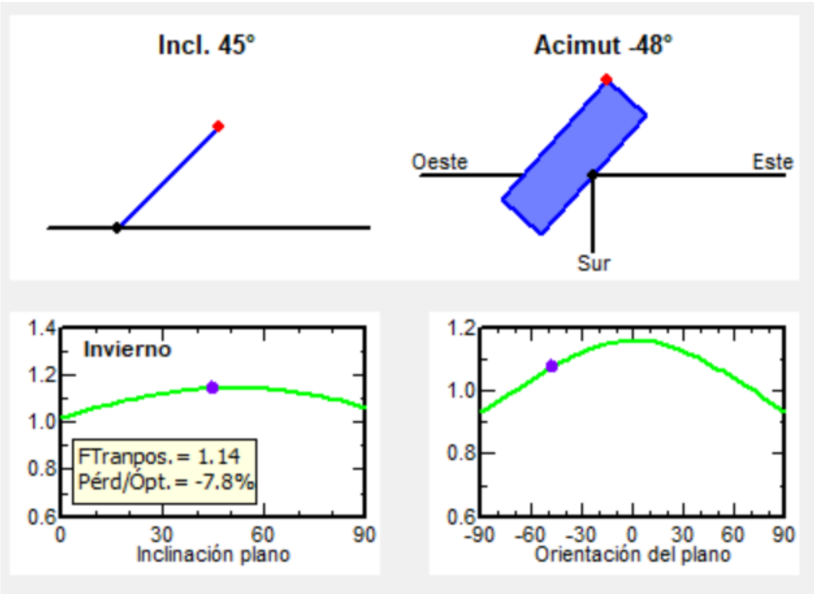


Figure 5.14. Optimal inclination and orientation for Petit Lys ([9])

5.4.3. Selection of PV panels

To choose the solar panels that will be placed in the installation, several considerations has been taken into account. The main characteristics that need to be decided are the type of solar cell, the power, the dimensions and the voltage.

As mentioned before, the most used solar panels are the polycrystalline ones. Since they are cheaper and easier to find in the market, it was preferred to use this kind of panels.

Whilst doing a research of different panels, it was observed that the panels of highest power had a better ratio between the power and the surface. Since the limitation of the space in this project is an important issue and to reduce the selection of possible panels, the ones with higher power (usually 330 W) were chosen.

Finally, the same webpage was used to compare the possible panels, because this way, the comparison will be more reliable through different brands of PV panels. The chosen website is "AutoSolar Energy Solutions". This website has a wide range of solar panels and all of them include the price and the technical data sheet.

Six different panels were compared, all of them had very similar characteristics, but the chosen panel was a JA Solar Panel, the JAP72S01-330 model. The characteristics of the panels are shown in the following tables and the technical data sheet is attached in Annex A.

Cell	Polycrystalline
Weight	22 kg ± 3%
Dimensions	1.960x991x40 mm
Cable Cross Section Size	4 mm^2
Number of cells and connections	72 (6x12)

Table 5.2. Specifications of JAP72S01-330

Maximum System Voltage	1.000V/1.500V DC(IEC)
Operating Temperature	-40ºC ~ +85ºC
Maximum Series Fuse	20 A
Maximum Static Load, Front	54.000 Pa
Maximum Static Load, Back	24.000 Pa
NOCT	45 ± 2ºC

Table 5.3. Operating conditions of JAP72S01-330

Rated Maximum Power (P_{max})	330 W
Open Circuit Voltage (V_{oc})	46,40 V
Maximum Power Voltage (V_{mpp})	37,65 V
Short Circuit Current (I_{sc})	9,28 A
Maximum Power Current (I_{mpp})	8,77 A
Module Efficiency	17,0%

Table 5.4. Electrical Parameters at STC of JAP72S01-330

Rated Maximum Power (P_{max})	244 W
Open Circuit Voltage (V_{oc})	43,41 V
Maximum Power Voltage (V_{mpp})	35,03 V
Short Circuit Current (I_{sc})	7,40 A
Maximum Power Current (I_{mpp})	6,97 A

Table 5.5. Electrical Parameters at NOCT of JAP72S01-330

5.4.4. Assembly of panels

As it was mentioned in previous points, the panels are thought to be placed in the playground. For this reason, and especially because the playground is small, the structure needs to be high, like a pergola, in order not to lose space of the playground.

In the section of angle and orientation some pictures of the possible space for the solar panels where shown. In Escola Lys, that place is used for the playground now, so in that case it is important that the pergola is at least 3 meters high since the kids need to be able to be under that structure. On the other side, in Petit Lys, that space is used to store some things, so it doesn't need to be that tall.

For Escola Lys, the available space (measured from the plan view) is 10x4 meters. Since in this case, the optimal inclination is 30º, the final area for the panels will be 10x4,61 meters, which equals to a surface of 46,1 m^2. Now, it is needed to calculate how many panels will fit in that space. With the measures of the panels available in the technical data sheet, we obtain the maximum value of panels that can be placed which is an array of 20 panels (4 rows of 5 panels).

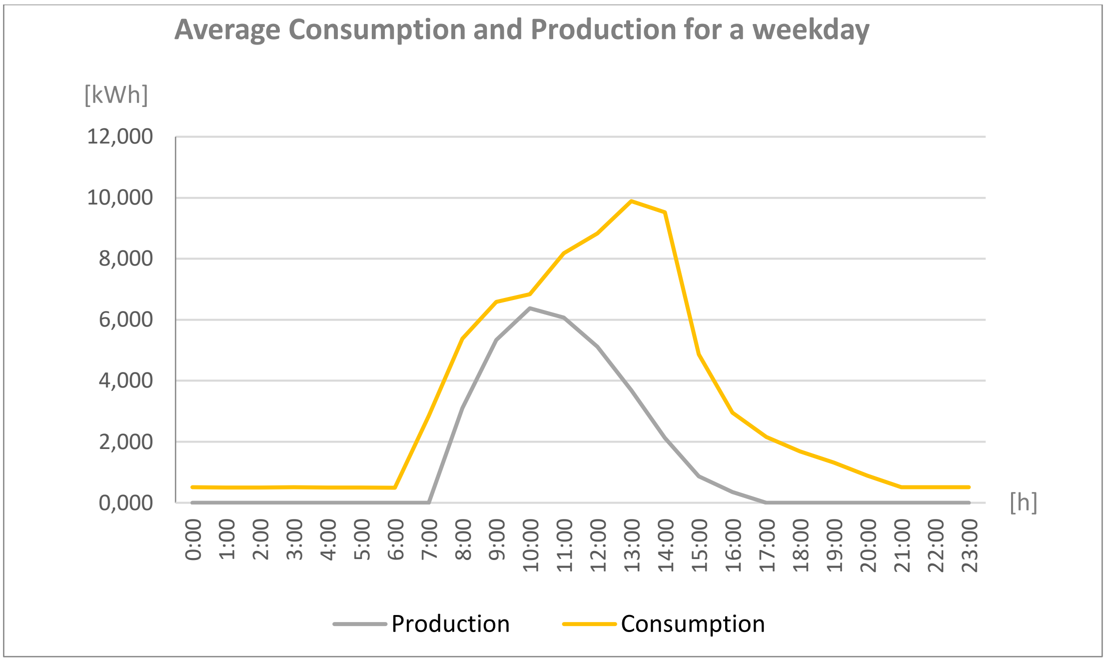
The same process is done for the space in Petit Lys. In this case, the measured space in plain view is 10x6 meters, with the optimal inclination of 45º, the available space for the solar panels will be 10x8,48 meters, the total surface is 84,8 m^2. Now the maximum possible array consists of 40 panels (8 rows of 5 panels).

In the case of Petit Lys, the number of panels that could be installed is quite big. Despite it may seem that using the maximum number of panels is the best option, it must be confirmed. To do so, a simple pre study of the demand that the panels will cover will be done. This study will be helpful to check the best solution considering the economic factor. It will be done for 40 and 30 panels.

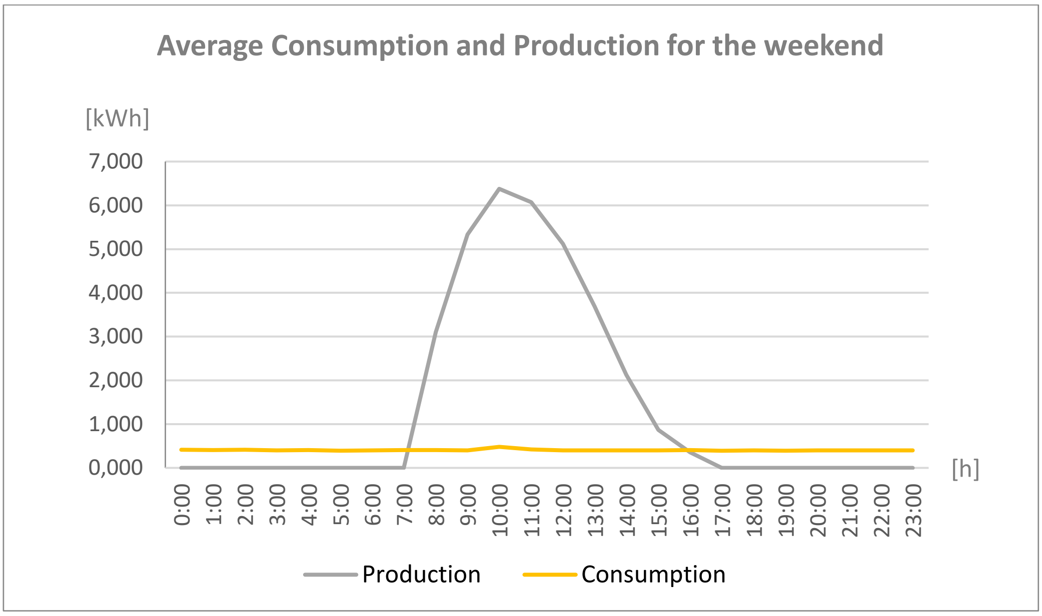
Ideally, this study would be done for the hourly production and consumption for the whole year. However, as it has already been mentioned, the only available hourly data is from November. Therefore, it will only be calculated for one month.

The demand profile has already been obtained in the previous points. Now, with the help of PVsyst, the values of the production must be obtained; later on, it will be explained with more detail the steps used to do a simulation in PVsyst.

Combining the values of the consumption and the production, a graph for an average day of the week and a graph for the weekend were created for each situation (40 and 30 panels) in Petit Lys. Here we can see the results:

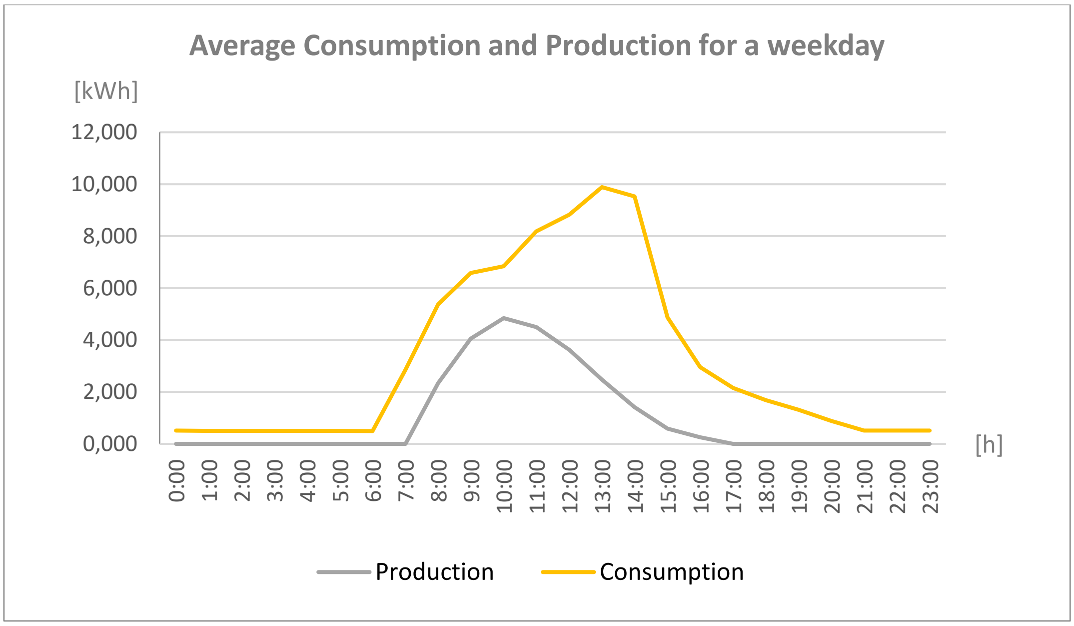


Graph 5.4. Average profile for a weekday with 40 Panels (Petit Lys)

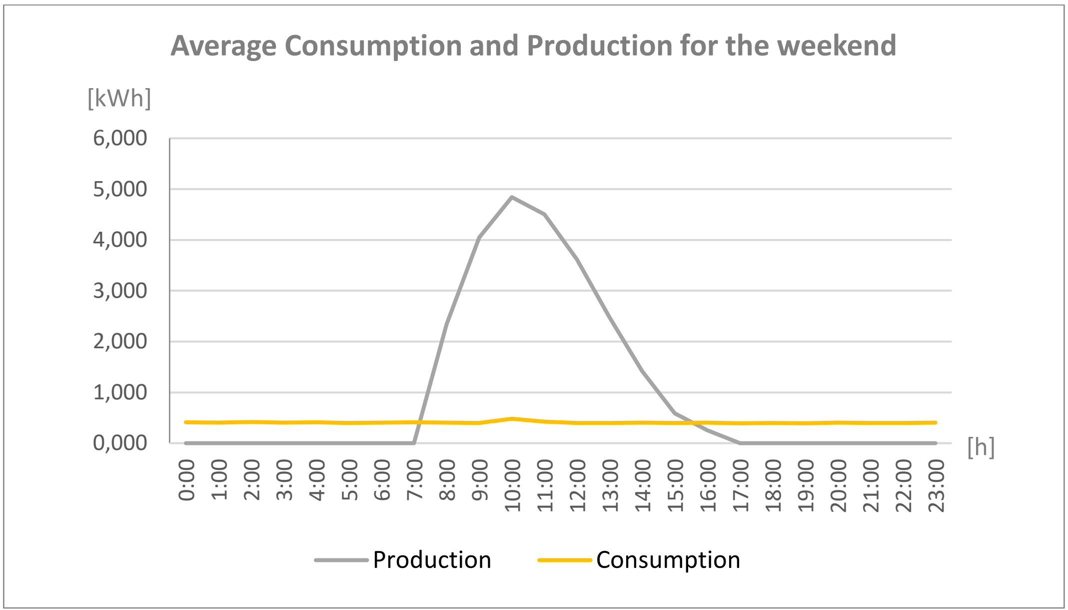


Graph 5.5. Average profile for the weekend with 40 Panels (Petit Lys)

With 40 panels during the weekdays, the demand is not covered completely and there are no surpluses. The production profile adapts very well to the consumption.



Graph 5.6. Average profile for a weekday with 30 Panels (Petit Lys)



Graph 5.7. Average profile for the weekend with 30 Panels (Petit Lys)

The only difference with these last two graphs is that the curve of the production is smaller.

At first sight, it can be seen that the installation with 40 panels adapts better to the profile demand of the weekdays, which translates into a bigger saving in the electricity bill. Also, it can be said that, in average, there will only be surpluses during the weekend.

Finally, an average of the price of the electricity has been calculated. This needed to be done because the prices from the different companies that the school has contracted are not the same. The price is divided between a fixed term that corresponds to the contracted power and the renting of the equipment, a variable term that corresponds to the energy consumed and the taxes. In the following table we can see the average values:

Contracted power [€]	454,72
Rent of equipment [€]	29,23
Electricity cost [€/kWh]	0,125997
Electricity tax [%]	5,113
IVA [%]	21

Table 5.6. Main values of the electricity cost

The surpluses of electricity are paid at 0,5 €/kWh and have the tax of Electricity Production Value (IVPEE) of 7% and the toll generation of 0,5 €/MWh.

With this information, a basic economic study can be done, where it is only included the cost of the equipment (PV panels and inverters) and the potential savings that the installation could have. The benefits have been calculated as the savings in buying electricity, at the cost of the table showed above, and the value obtained for the energy injected to the grid. It has been counted that the year 2019 has 250 working days and 115 that are weekends or holidays. Also, from these 250 working days, 23 correspond to July and 21 to August, so they have been considered with the profile of the weekends.

This is only a simple study to check which solution is better studying the parts that vary the most, therefore the installation, the hours dedicated to the project and the taxes, among other things haven't been considered.

In the following tables we can see the cost of the equipment and the saving for each case:

	40 panels	**30 panels**
Cost panels [€]	6.231,60	4.673,70
Cost inverter [€]	2.899,18	2.440,88
Savings [€]	1.098,34	793,50

Table 5.7. Costs and Savings for each situation in Petit Lys

With these values, the payback of the equipment for the option of 40 panels is 8,31 years whilst for the second option is 8,91 years. It is not a big difference but still is better to install as much panels as possible whilst being under the desired peak capacity.

5.4.5. Selection of the inverter

To choose an inverter that fits the PV system, it is important to check some parameters that are available on the technical data sheet:

- Rated power output: this is the operating power value that the inverter is designed for. The power of the photovoltaic generator needs to be contained in this range.

- Maximum Input Power: this parameter must never be exceeded by the power output from the PV array.

- Maximum Open Circuit Voltage: Again, the V_{oc} from the array must be less than the inverter's limit. For the array it is calculated as the V_{oc} under 1.000 W/m^2 and at the lower temperature possible (in Europe is fixed at -10ºC).

- Frequency output: In Europe, the operating frequency of power supply is 50 Hz.

- Efficiency: it is the percentage of DC power from the solar panels that is converted to AC power. Nowadays good inverters have an efficiency higher than the 95% at full load.

For both cases, the inverter selected is a model of SMA, the Sunny Boy 6.0 (with the reference SB6.0-1AV-41). This inverter has two independent MPP inputs with two string per input. The data sheet is attached in Annex B.

With the SunnyDesignWeb (webpage of SMA) it is possible to a do a simulation of a PV system. For the inverter, it verifies that the parameters of the PV array suit the inverter. In the first case, there will be 2 strings of 10 panels each, connected to different MPP inputs.

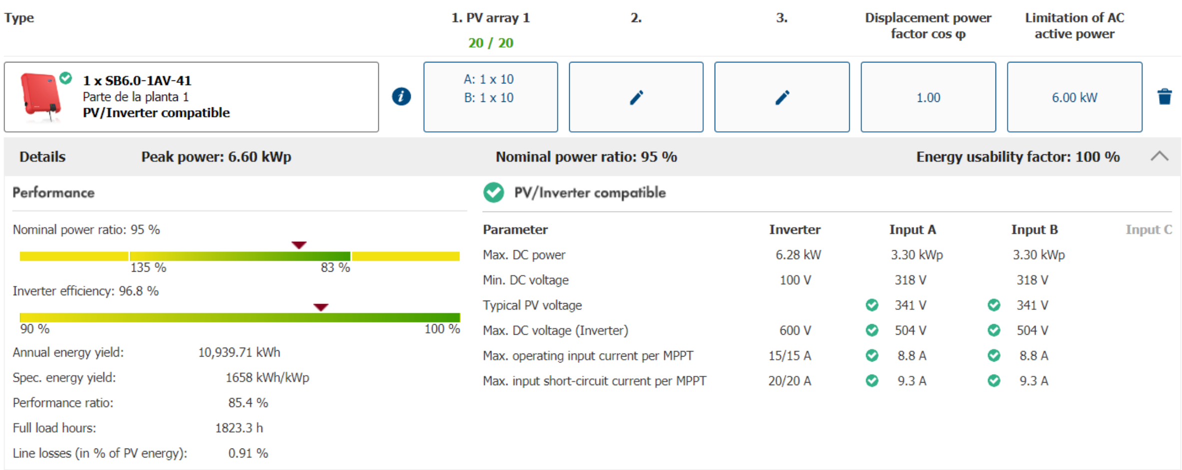


Figure 5.15. Details of the inverter connection for Escola Lys ([11], 2019)

In the following table, the values for the current voltage and power of the assembly will be shown:

P_{TOTAL}	6.600 W
$I_{INPUT\ A} = I_{INPUT\ B}$	8,77 A
$V_{INPUT\ A} = V_{INPUT\ B}$	376,5 V

Table 5.8. Main Electrical Values for the PV array of Escola Lys

In the second case, for Petit Lys, two inverters of the same model will be used.

The connection done in this case is again symmetric, 4 strings of 10 modules, 2 strings connected to one inverter and 2 strings for the other one. With this configuration, the values obtained are shown in the next figure:

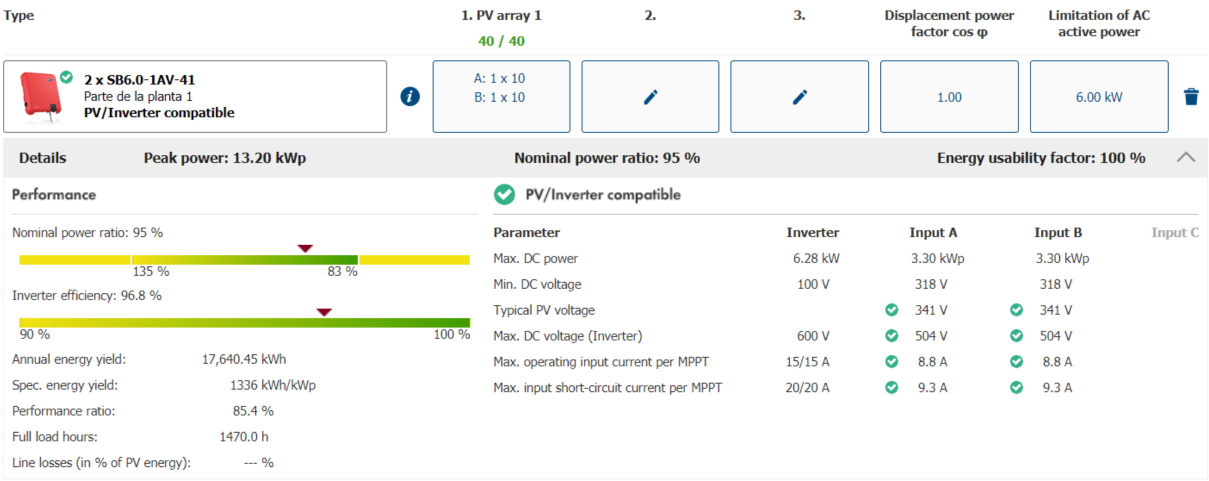


Figure 5.16. Details of the inverter connection for Petit Lys ([11], 2019)

Now, the values for the PV array are the following ones:

P_{TOTAL}	13.200 W
$I_{INPUT\ A} = I_{INPUT\ B}$ (for each inverter)	8,77 A
$V_{INPUT\ A} = V_{INPUT\ B}$ (for each inverter)	376,5 V

Table 5.9. Main Electrical Values for the PV array of Petit Lys

The values from SunnyDesign have been obtained with the following considerations:

- The typical PV voltage is calculated for the NOCT (which for this programme is 48ºC, it varies a bit because the data sheet from the panel available in the website is from a different year.
- The Min. DC voltage is the MPP voltage of the string at the currently set maximum cell temperature (63 ºC)
- The Max. DC voltage is the open-circuit voltage of the string at set minimum cell temperature (-1ºC).
- The Max. Input short-circuit current of the inverter per MPP tracking.

5.5. Design of the Electrical Connection

5.5.1. Wiring installation

The design of the wiring installation can be divided in two parts: the part of direct current and the part for altern current. The main characteristics of a cable are the material of the conductor and the material and section of the insulator.

For deciding the section of the insulator, two different criterium must be considered:

- Criteria of maximum permissible current or of heating: in the worst predictable conditions, the temperature of the insulation should not be excessive.

- Criterion of the voltage drop: In order to supply the appropriate voltage to the receivers and to avoid excessive losses, the voltage drop cannot exceed a maximum value set by the Regulation.

The material used for all the conductors will be copper and they will have the adequate section for avoiding voltage drop and overheating. In particular, for any working condition, the conductors must have a sufficient section so that the voltage drop is less than 1,5%.

Also, the cable must have the necessary length so as not to generate stress on the various elements or the possibility of hooking through normal traffic of people. All continuous wiring shall be double insulated and suitable for use outdoors, in the air or buried, in accordance with the UNE 21123 standard.

DC wiring design

For the DC sections, conductors of type 0,6/1 kV of copper with 2 x XLPE insulation will be used. The type of installation will be “Multi-conductor cables in pipes in surface mounting or recessed on site” according to the definition of REBT in ITC-BT-19 standard.

A	Conductores aislados en tubos empotrados en paredes aislantes		3x PVC	2x PVC		3x XLPE o EPR	2x XLPE o EPR					
A2	Cables multiconductores en tubos empotrados en paredes aislantes	3x PVC	2x PVC		3x XLPE o EPR	2x XLPE o EPR						
B	Conductores aislados en tubos[3] en montaje superficial o empotrados en obra				3x PVC	2x PVC			3x XLPE o EPR	2x XLPE o EPR		
B2	Cables multiconductores en tubos[2] en montaje superficial o emprotrados en obra			3x PVC	2x PVC		3x XLPE o EPR		2x XLPE o EPR			
C	Cables multiconductores directamente sobre la pared[3]					3x PVC	2x PVC		3x XLPE o EPR	2x XLPE o EPR		
E	Cables multiconductores al aire libre[4] Distancia a la pared no inferior a 0.3D[5]						3x PVC		2x PVC	3x XLPE o EPR	2x XLPE o EPR	
F	Cables unipolares en contacto mutuo[4] Distancia a la pared no inferior a D[5]							3x PVC			3x XLPE o EPR[1]	
G	Cables unipolares separados mínimo D[5]									3x PVC[1]		3x XLPE o EPR
Cobre	mm^2	1	2	3	4	5	6	7	8	9	10	11
	1,5	11	11,5	13	13,5	15	16	-	18	21	24	-
	2,5	15	16	17,5	18,5	21	22	-	25	29	33	-
	4	20	21	23	24	27	30	-	34	38	45	-
	6	25	27	30	32	36	37	-	44	49	57	-
	10	34	37	40	44	50	52	-	60	68	76	-
	16	45	49	54	59	66	70	-	80	91	105	-
	25	59	64	70	77	84	88	96	106	116	123	166
	35		77	86	96	104	110	119	131	144	154	206
	50		94	103	117	125	133	145	159	175	188	250
	70				149	160	171	188	202	224	244	321
	95				180	194	207	230	245	271	296	391
	120				208	225	240	267	284	314	348	455
	150				236	260	278	310	338	363	404	525
	185				268	297	317	354	386	415	464	601
	240				315	350	374	419	455	490	552	711
	300				360	404	423	484	524	565	640	821

Table 5.10. Permissible intensities (A) in air 40°C. Number of conductors with load and nature of insulation.

For the calculation of the section by the criterium of voltage drop, in the DC part, the following equation will be used:

$$S = 2 \cdot \frac{\rho \cdot l \cdot I}{u}$$

Where:

- S is the theoretical section of the conductor in [mm^2].
- ρ is the resistivity of the element that forms the conductor, in this case it is always used copper and its resistivity is 0,0172Ω*mm^2/m.
- l is the length of the conductor [m].
- I is the maximum current that will circulate through the conductors and is the current of short circuit for the panels [A].
- u is the voltage drop [V] that the conductors may have at most. According to the IDAE Technical Specification, the maximum voltage drop allowed is 1,5%.

The DC installation is the same for both cases, it only changes the fact that in Petit Lys the size is the double but since there are two inverters, the currents and voltages are the same for all the strings. Therefore, the same calculations work for Escola Lys and Petit. It has been considered a generic length of 30 meters for each string, where it is included all the wiring between the panels and until the inputs of the inverters.

For the Criterium of Permissible Current, also the current of short-circuit of the panels must be considered, which is 9,28 A. For the cable chosen, the section should be 1,5 mm^2.

Now, for the voltage drop criterium, the following table is obtained:

	l (m)	I (A)	V (V)	u (V)	Section (mm^2)
DC wiring	30	9,28	376,5	5,65	1,69

Table 5.11. Section by Criterium of Voltage Drop for Escola Lys and Petit Lys

The nearest superior section must be chosen, which is 2,5 mm^2. Considering the two criteriums, the most restrictive section is the one that must be used, this means that for all the DC connections for both installations, Escola Lys and Petit Lys, the sizing of the cables will be 2,5mm^2.

<u>AC wiring design</u>

For the AC sections, conductors of type 0,6/1 kV of copper with 3 x XLPE insulation will be used. The type of installation will be “Multi-conductor cables in pipes in surface mounting or recessed on site” according to the definition of REBT in ITC-BT-19 standard.

A		Conductores aislados en tubos empotrados en paredes aislantes		3x PVC	2x PVC		3x XLPE o EPR	2x XLPE o EPR					
A2		Cables multiconductores en tubos empotrados en paredes aislantes	3x PVC	2x PVC		3x XLPE o EPR	2x XLPE o EPR						
B		Conductores aislados en tubos[3] en montaje superficial o empotrados en obra				3x PVC	2x PVC			3x XLPE o EPR	2x XLPE o EPR		
B2		Cables multiconductores en tubos[2] en montaje superficial o emprotrados en obra			3x PVC	2x PVC		3x XLPE o EPR		2x XLPE o EPR			
C		Cables multiconductores directamente sobre la pared[3]					3x PVC	2x PVC		3x XLPE o EPR	2x XLPE o EPR		
E		Cables multiconductores al aire libre[4] Distancia a la pared no inferior a 0.3D[5]						3x PVC		2x PVC	3x XLPE o EPR	2x XLPE o EPR	
F		Cables unipolares en contacto mutuo[4] Distancia a la pared no inferior a D[5]							3x PVC			3x XLPE o EPR[1]	
G		Cables unipolares separados minimo D[5]									3x PVC[1]		3x XLPE o EPR
		mm²	1	2	3	4	5	6	7	8	9	10	11
Cobre		1,5	11	11,5	13	13,5	15	16	-	18	21	24	-
		2,5	15	16	17,5	18,5	21	22	-	25	29	33	-
		4	20	21	23	24	27	30	-	34	38	45	-
		6	25	27	30	32	36	37	-	44	49	57	-
		10	34	37	40	44	50	52	-	60	68	76	-
		16	45	49	54	59	66	70	-	80	91	105	-
		25	59	64	70	77	84	88	96	106	116	123	166
		35		77	86	96	104	110	119	131	144	154	206
		50		94	103	117	125	133	145	159	175	188	250
		70				149	160	171	188	202	224	244	321
		95				180	194	207	230	245	271	296	391
		120				208	225	240	267	284	314	348	455
		150				236	260	278	310	338	363	404	525
		185				268	297	317	354	386	415	464	601
		240				315	350	374	419	455	490	552	711
		300				360	404	423	484	524	565	640	821

Table 5.12. Permissible intensities (A) in air 40°C. Number of conductors with load and nature of insulation.

In this section, the sections may vary because there is one inverter for Escola Lys and two inverters for Petit Lys.

For the permissible intensities criterium, the maximum output current of the inverter must be checked. This value, given in the Technical Data Sheet from Annex B, is 26,1 A, therefore with this criterium, the section of the conductor should be 4 mm^2 for Escola Lys and 16 mm^2 for Petit Lys

Now, for the voltage drop criterium, since the installation is monophasic, the same equation as before is used. The main difference is that the voltage that must be considered is 230 V, which is the line voltage of the network. As for the previous criterium, the maximum output current of the inverter is considered.

The following table is obtained for both cases:

	l (m)	I (A)	V (V)	u (V)	Section (mm^2)
AC wiring: Escola Lys	20	26,1	230	3,45	5,20
AC wiring: Petit Lys	20	52,2	230	3,45	10,41

Table 5.13. Section by Criterium of Admissible Current for Escola Lys and Petit Lys

Following the same procedure, the section for the cable in the AC side will be 6 mm^2 for Escola Lys and 16 mm^2 for Petit Lys.

5.5.2. Earthing system

The earthing is the direct electrical connection, without fuses or any protection, of a part of the electrical circuit or a conductive part not belonging to it by means of an earthing with an electrode or groups of electrodes buried in the ground.

According to ITC-BT-18 "Earthing installations", the earthing of an installation consists of:

- **Earthing:** they are electrodes formed by bars, flat tubes or meshes that are in direct contact with the earth where the leakage current that may occur at some point will be drained, these earthing must be made of specific materials and will be buried at a depth suitable for the characteristics of the installation to be protected.

- **Earth conductors:** these are the conductors that connect the electrode of the earth installation to the main earth terminal. The section of these conductors must meet the requirements of the protection conductors.

- **Earthing terminals:** they are the union of all the protection conductors of the installation that come from the different elements or masses to be protected. A device that allows measuring the resistance of the corresponding earth connection must be provided on the earth conductors and in an accessible place.

  This device may be combined with the main earth terminal, it must necessarily be removable by means of a tool, it must be mechanically safe and must ensure electrical continuity.

- **Protection conductors:** they serve to electrically join the masses of an installation to certain elements, in order to ensure protection against indirect contacts. They will join the masses to the earthing terminal and with it the earthing conductor.

  The section of the protection conductors must follow the specifications of the next table:

Sección de los conductores de fase de la instalación S (mm^2)	Sección mínima de los conductores de protección S_p (mm^2)
$S \leq 16$	$S_p = S$
$16 < S \leq 35$	$S_p = 16$
$S > 35$	$S_p = S/2$

Table 5.14. Relationship between the sections of the protective and phase conductors

All the sections of the conductors of the installation are smaller or equal to 16 mm^2, therefore, the section for the protection conductors will be the same as the phase wiring connection.

In the following table, the sections of the protection cables for each situation are displayed:

	Escola Lys	Petit Lys
DC connections	2,5 mm^2	2,5 mm^2
AC connections	6 mm^2	16 mm^2

Table 5.15. Sections for protection cables

5.5.3. Protections

The REBT (art. 16.4) indicates that the protection systems for internal installations or receivers must prevent the effects of overcurrent and surges protecting the materials and equipment installed.

According to the ITC-BT-22, any circuit must be protected for the effects of the overcurrent that may happen. Overcurrent can be caused by:

- Overloads caused by the equipment or high impedance insulation defects.
- Short-circuits.
- Atmospheric electric discharges.

The ITC-BT-23 explains the protections that should be used for surges. Indoor installations must be protected against transient surges transmitted by distribution networks and which arise, mainly as a result of:

- Atmospheric electric discharges.
- Network switching.
- Defects in electrical networks.

In addition, the installation must be protected against direct and indirect contacts. The ITC-BT-24 describes the measures to be considered for this case.

The calculation of protections will be carried out independently for each of the circuits that form the installation, differentiating between sections of direct current and alternating current.

<u>DC protections</u>

- **Fuses:** Each string will have two fuses of identical electrical characteristics, one for the positive polarity conductor and the other for the negative polarity conductor. They will protect the strings against overcurrents.

  According to the ITC-BT-22 a device protects a conductor against overloads if the following conditions are verified:

$$I_B \leq I_N \leq I_Z$$

$$I_2 \leq 1{,}45 \cdot I_Z$$

Where:

- I_B is the current for which the circuit has been designed.
- I_Z is the maximum permissible current (in this case it is he maximum short-circuit current that the inverter can handle)
- I_N is the rated current of the protection device.
- I_2 is the current that ensures the performance of the protection device for a long time.

In the fuse protection of type gG, I_2 depends on I_N:

$$I_2 = 1{,}6 \cdot I_N \quad if \quad I_N \geq 16\ A$$

$$I_2 = 1{,}9 \cdot I_N \quad if \quad 4\ A \leq\ I_N \leq 16\ A$$

$$I_2 = 2{,}1 \cdot I_N \quad if \quad I_N \leq 4\ A$$

Since all the strings are the same for both installations the fuse chosen will be one of 10 A, because it accomplishes all the equations:

$$8{,}77\ A \leq I_N \leq 15\ A$$

$$I_2 \leq 1{,}45 \cdot 15\ A = 21{,}75\ A$$

$$I_2 = 1{,}9 \cdot 10 = 19\ A$$

- **Surge protector:** there will be one surge protector before each input of the inverter. As it is mentioned in the ITC-BT-23 there are three different types of surge protectors, the type of class II will be used in this project.
  To choose the surge protector the open voltage of each string must be considered. The V_{oc} of the panels is 46,40 V, then the V_{oc} of the string is 460 V.

AC protections

- **Magnetothermal:** A magnetothermal is a circuit breaker that combines two disconnecting systems: a fast-acting magnetic device designed to act in the event of a short-circuit (instantaneous trip) and a slow-responding thermal device to protect against overloads.
  Again, as it is said in the ITC-BT-22 the same equations that has been used for the fuses must be used to determine the nominal current of this gadget.
  Nevertheless, the second condition is always fulfilled because I_2 is always calculate as $I_2 = 1{,}45 \cdot I_N$.
  In this case, I_B corresponds to the output current of the inverter (26,1 A) in Escola Lys and to the sum of both inverters (52,2 A) and I_Z corresponds to the maximum current that the connector can support (37 A for Escola Lys and 70 A for Petit Lys).
  Magnetothermal have values that are already normalized, for Escola Lys the one that should be chosen is one of 32 A and for Petit Lys, one of 63 A.

- **Differential switch:** Differential switches provide protection to people against electric shocks, both in the case of direct contacts and indirect contacts and protection of the installations as they detect earth leakage by measuring the current flowing through the conductors.
  According to ITC-BT-25, differential switches must have a maximum differential-residual current of 30mA for domestic applications and 300mA for other applications and rated intensity than that of the general switch. The nominal current of the differential switch will be greater than 26,1 A for Escola Lys and greater than 56,2 A for Petit Lys.

- **Disconnector:** A disconnector is a safety element that is intended to isolate or ground parts of a circuit during repairs and modifications. To choose the disconnector, it is needed to use the maximum current of the circuit.
  Again, this is the maximum current of the inverter or inverters (26,1 A for Escola Lys and 52,2 A for Petit Lys).

6. Simulation

In order to simulate the system, the programme PVsyst was used. This is a software used to define photovoltaic systems. It allows to analyse different configurations and to evaluate the results, including the losses, and identify the best possible solution.

First of all, the location needed to be introduced since Barcelona was not in the database. To define a new location, it was only needed to introduce the coordinates and import the monthly meteorological data.

Once the location is created, the next step is to start the project design. In this particular case, a Grid-Connected system is chosen. To define the project, it is needed to introduce the orientation of the panels, select a PV module and an inverter that will also be used to define the number of modules and strings.

The PV module and the inverter had been chosen in the previous points. Since they are from well-known fabricants, both the modules and inverters where already in the database of the software. Nevertheless, the versions where a bit old, so the parameters where updated according to the ones in the technical data sheet.

The next step is to implement the detailed losses. Most of them are already predetermined by PVsyst. The only ones that needed to be introduced were the losses caused by the possible dirt or dust, the losses for the wiring and the losses for the shadings.

The losses considered for the dirt or dust are a 4% because the panels have in both cases an inclination equal or greater than 30º. For the wiring ones, the material, section and length of the cables calculated in the point 5.3.6 were introduced.

Since the location of the two schools is surrounded by buildings, the losses for the near shadings must be studied carefully. First, the buildings were measured with "Sede Electronica del Catastro" and the height of the buildings was approximated (it was counted 3 meters for each floor). Then, a 3D representation was implemented into PVsyst, the near buildings of the two schools were introduced. The building of the schools is painted in blue and the playgrounds in orange. Also, the PV panels are displayed with the orientation and inclination obtained in the previous points.

The construction of this 3D scene is approximated, due to this, the losses calculated by PVsyst may have some discrepancies with the reality, but they will be useful to make a study and decide which is the best location.

In the following pictures we can the 3D representation made with PVsyst for each case with the near buildings and the possible location for the PV array:

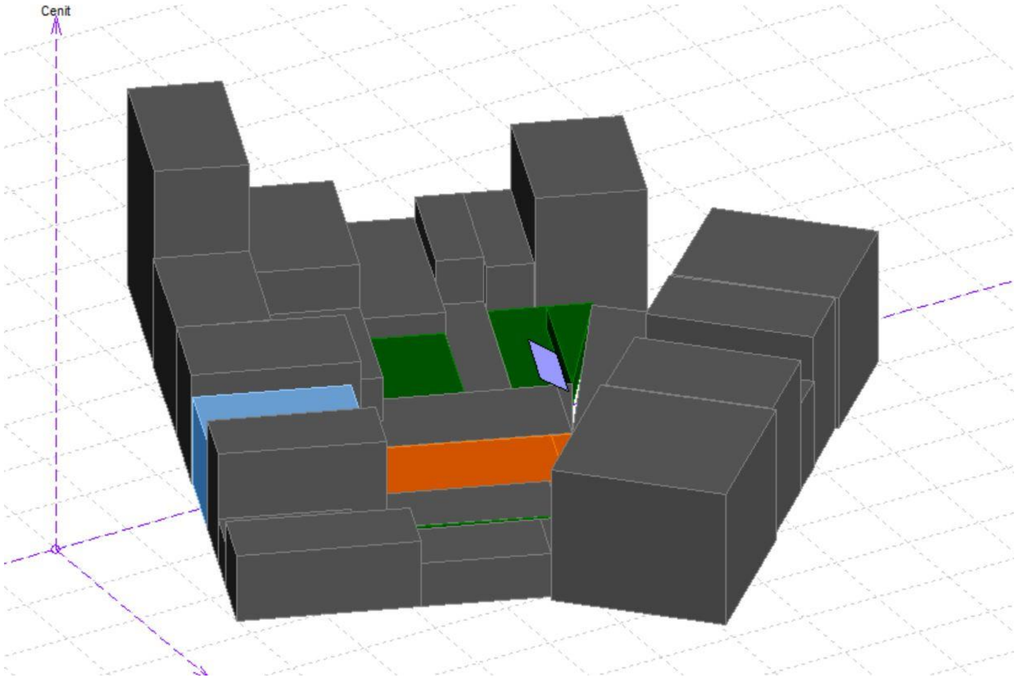


Figure 6.1. 3D representation of possible location for the panels for Escola Lys ([9])

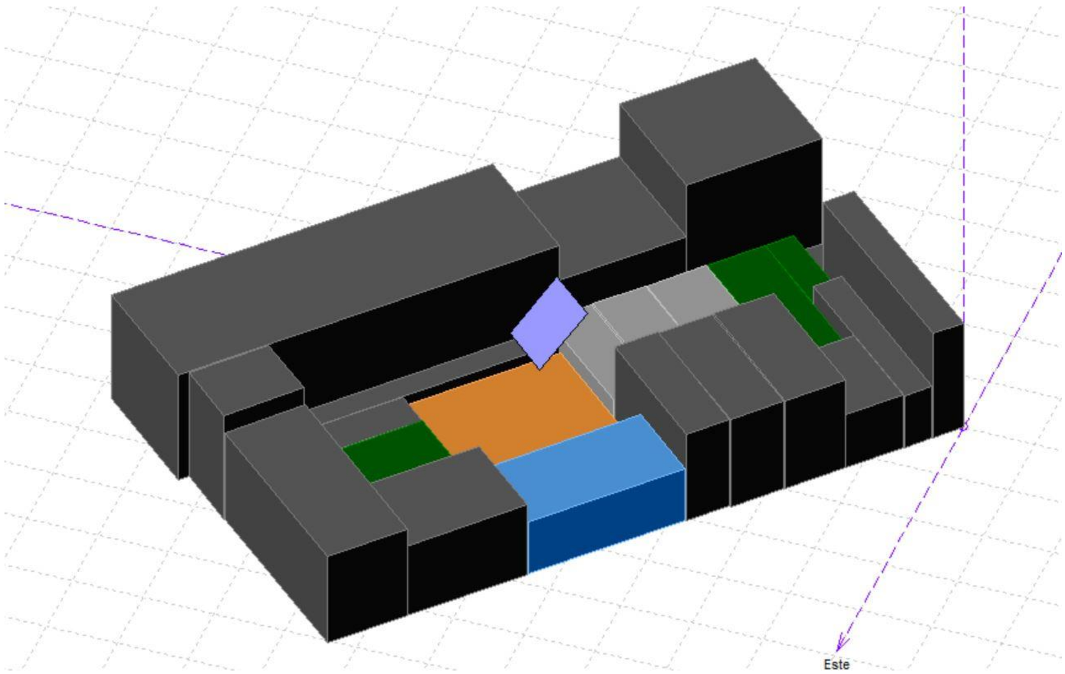


Figure 6.2. 3D representation of possible location for the panels for Petit Lys ([9])

Once all the system was designed it is only needed to start the simulation. The main results of the simulations are displayed below.

Project :	**Escola Lys**			
Simulation variant :	**Simulación 1**			
Main system parameters	System type	**Grid-Connected**		
Near Shadings	Linear shadings			
PV Field Orientation	tilt	30°	azimuth	-69°
PV modules	Model	JAP7-72-330/SC	Pnom	330 Wp
PV Array	Nb. of modules	20	Pnom total	**6.60 kWp**
Inverter	Model	Sunny Boy 6.0 230V	Pnom	6.00 kW ac
User's needs	Unlimited load (grid)			
Main simulation results				
System Production	**Produced Energy**	**6900 kWh/year**	Specific prod.	1045 kWh/kWp/year
	Performance Ratio PR	61.5 %		

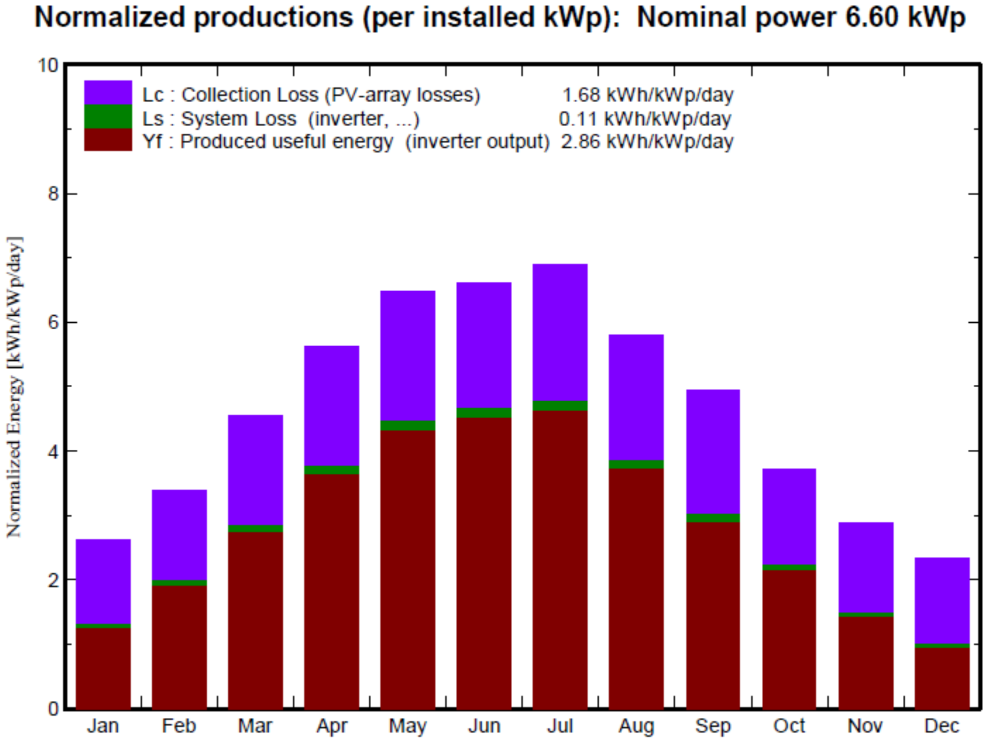
Table 6.1. Main characteristics of the simulation for Escola Lys ([9])

Project :	**Petit Lys**			
Simulation variant :	**Version 1**			
Main system parameters	System type	**Grid-Connected**		
Near Shadings	Linear shadings			
PV Field Orientation	tilt	45°	azimuth	-48°
PV modules	Model	JAP7-72-330/SC	Pnom	330 Wp
PV Array	Nb. of modules	40	Pnom total	**13.20 kWp**
Inverter	Model	Sunny Boy 6.0 230V	Pnom	6.00 kW ac
Inverter pack	Nb. of units	2.0	Pnom total	**12.00 kW ac**
User's needs	Unlimited load (grid)			
Main simulation results				
System Production	**Produced Energy**	**17109470 W/year**	Specific prod.	1296 kWh/kWp/year
	Performance Ratio PR	72.6 %		

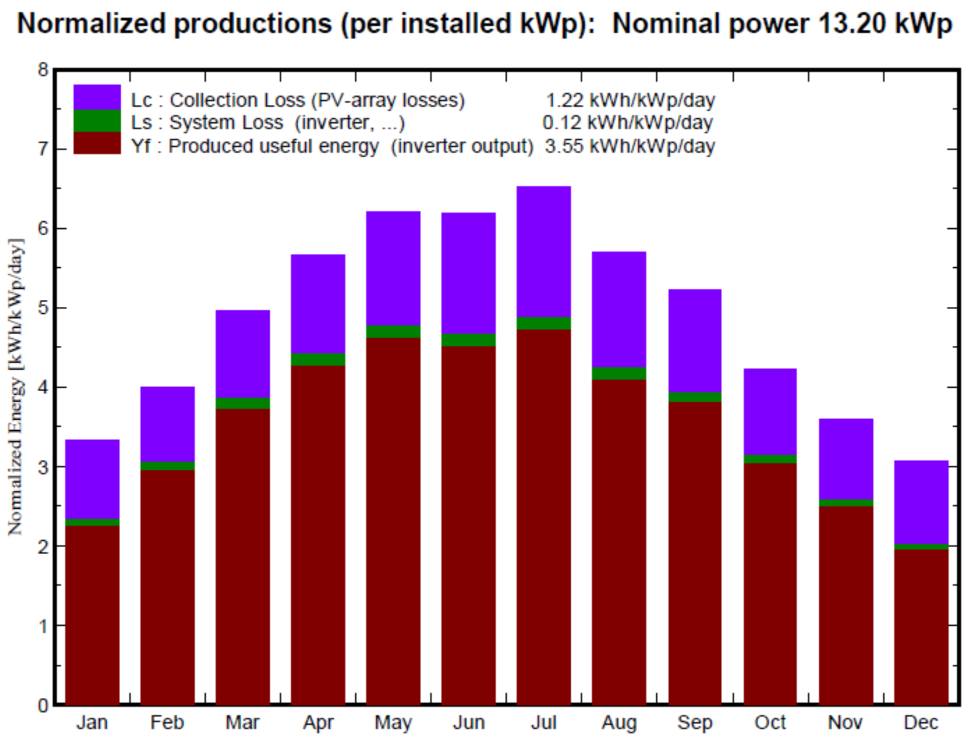
Table 6.2. Main characteristics of the simulation for Petit Lys ([9])

In this two tables it is possible to see the main results of both simulations. From the start it could be supposed that the Installation for Petit Lys is better because the number of modules is bigger. Nevertheless, it was needed to check the performance ratio because the losses could make the system worst despite having more panels.

Here it can be proved that not only the total energy produced is greater but also the specific production and the PR is better.



Graph 6.1. Normalized production for Escola Lys ([9])



Graph 6.2. Normalized production for Petit Lys ([9])

In the graphs showed above it can be seen the produced energy and the losses for the different months of the year. The installation of Petit Lys is clearly better than the one for Escola Lys, despite this, the losses are still bigger than the desired for a PV installation.

To determine the causes of this losses the following diagrams will be helpful:

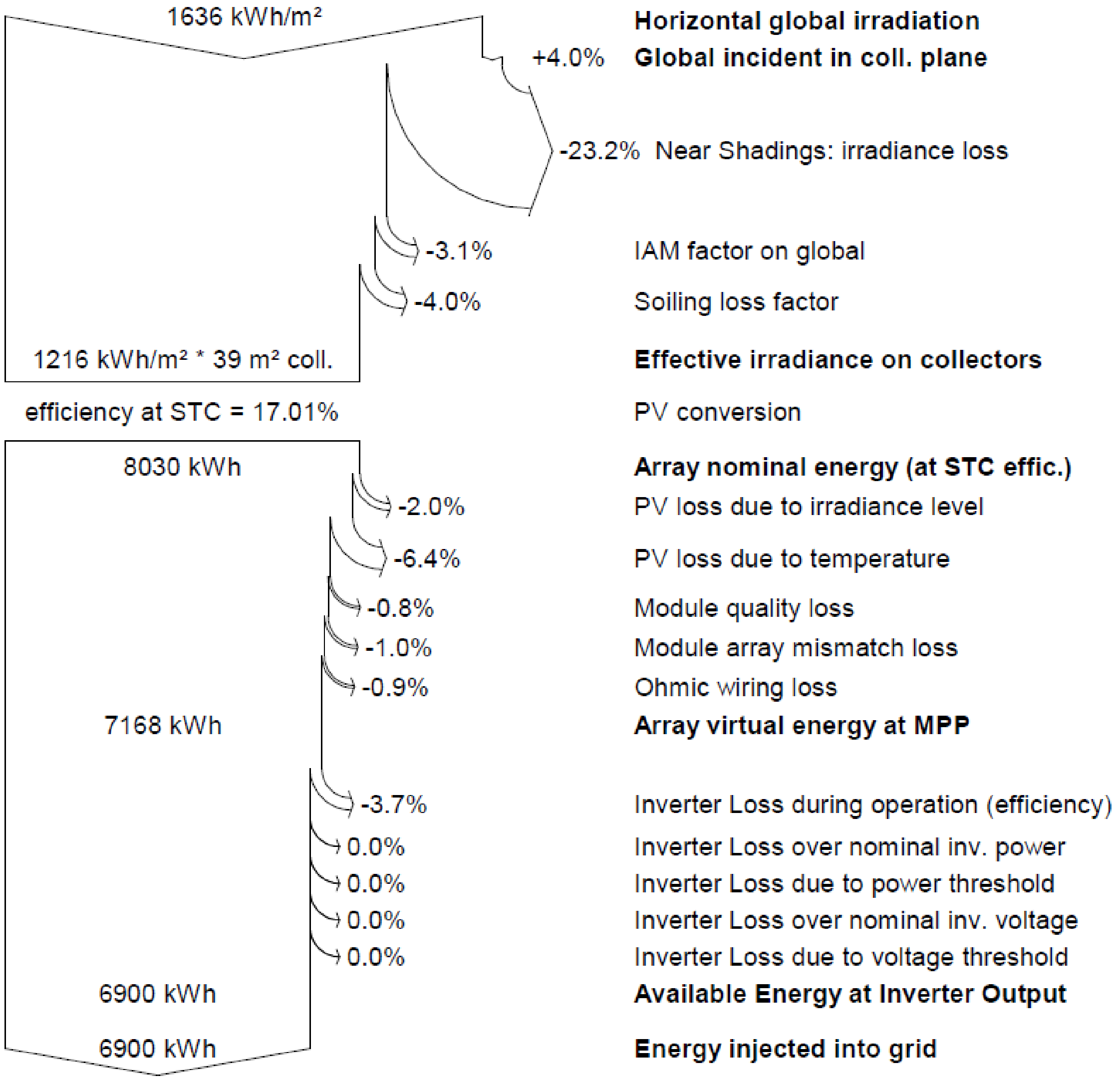


Figure 6.3. Detailed losses of the system for Escola Lys ([9])

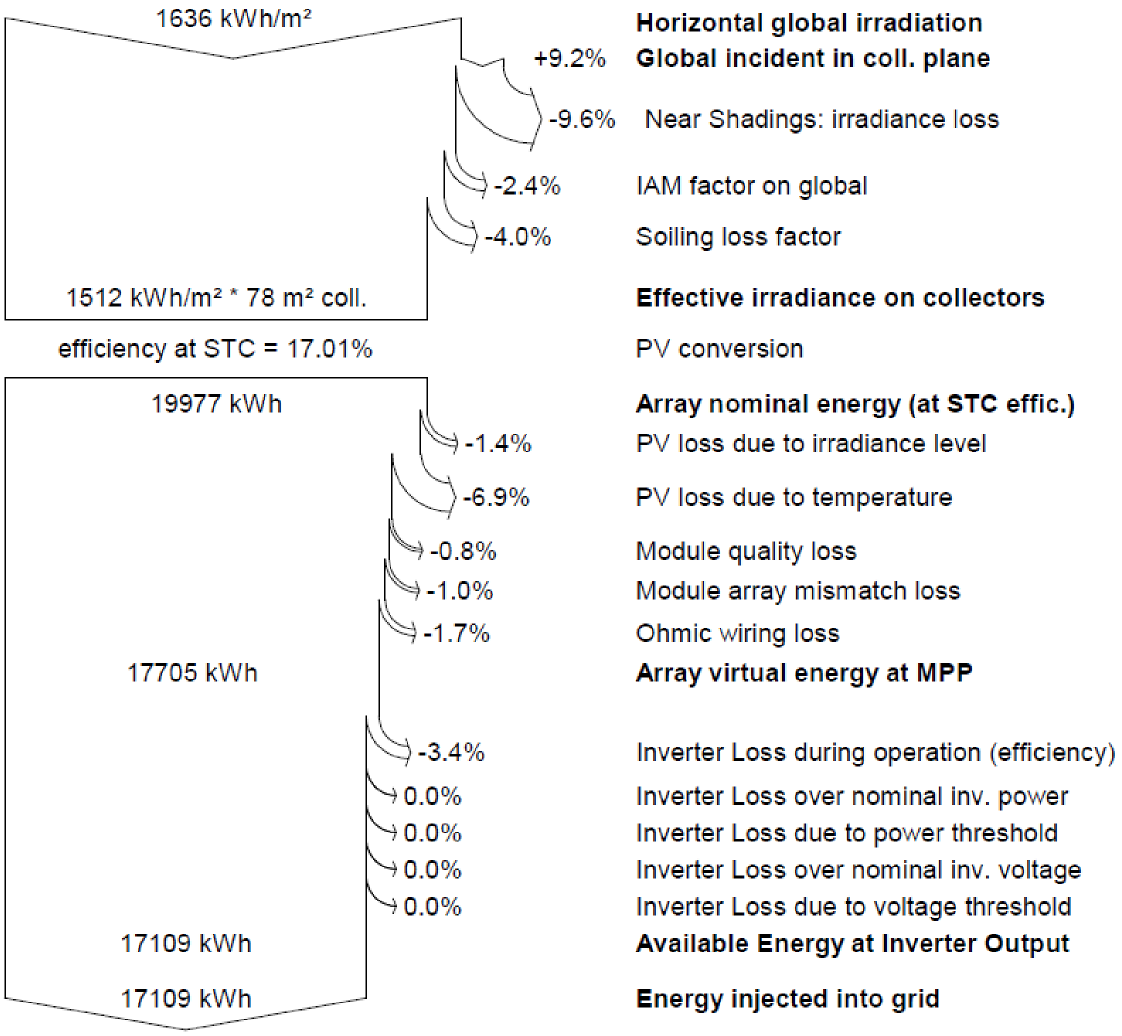


Figure 6.4. Detailed losses of the system for Petit Lys ([9])

One of the main concerns of this project was the location of the PV modules. Here it can be corroborated that the losses due to the near shadings are a big problem for both systems but especially for Escola Lys.

For all these reasons, the system for Petit Lys will be the one used to calculate the budget of the project.

7. Environmental impact

The environmental impact for a solar installation is almost null once the installation is finished, however the extraction of the materials and the construction do emit polluting substances. In this section, the materials used for a solar panel, the polluting substances emitted, the visual impact and the product life will be discussed.

7.1. Materials involved in a solar panel

The main parts of a solar panel are the following ones:

1. Silicon solar cells
2. Metal frame (typically aluminium)
3. Toughened glass
4. Encapsulation (EVA)
5. Polymer rear back sheet
6. Junction box (diodes and connectors)

Some elements, such as the metal frame, the toughened glass and the encapsulate are used to protect the PV cells from the weather conditions or impacts.

7.2. Polluting substances

It is true that once PV panels are operating, they produce zero carbon dioxide emissions. Despite this, during the manufacturing process and the transportation CO2 is emitted, therefore the environmental footprint is not zero.

Options	Direct emissions	Infrastructure & supply chain emissions	Biogenic CO_2 emissions and albedo effect	Methane emissions	Lifecycle emissions (incl. albedo effect)
	Min/Median/Max	Typical values			Min/Median/Max
Currently Commercially Available Technologies					
Coal—PC	670/760/870	9.6	0	47	740/820/910
Gas—Combined Cycle	350/370/490	1.6	0	91	410/490/650
Biomass—cofiring	n.a. [ii]	–	–	–	620/740/890 [iii]
Biomass—dedicated	n.a. [ii]	210	27	0	130/230/420 [iv]
Geothermal	0	45	0	0	6.0/38/79
Hydropower	0	19	0	88	1.0/24/2200
Nuclear	0	18	0	0	3.7/12/110
Concentrated Solar Power	0	29	0	0	8.8/27/63
Solar PV—rooftop	0	42	0	0	26/41/60
Solar PV—utility	0	66	0	0	18/48/180
Wind onshore	0	15	0	0	7.0/11/56
Wind offshore	0	17	0	0	8.0/12/35

Table 7.1. Emissions of electricity supply technologies (gCO_2 eq/kWh) ([10], 2019)

In the previous table the life-cycle emissions from different technologies can be compared. It is true that they are not null but still much lower than the conventional ways of obtaining electricity.

7.3. PV useful life

Nowadays, the product life of most PV panels is estimated between 25 and 30 years. The Solar photovoltaic deployment has grown exponentially since the early 2000s. Therefore, it will become essential to recycle solar panels once their product life is over.

At present, only the European Union (EU) has adopted PV-specific waste regulations. Most countries around the world classify PV panels as general or industrial waste. Therefore, reciclying policies must be implemented in the life-cycle of the PV panels.

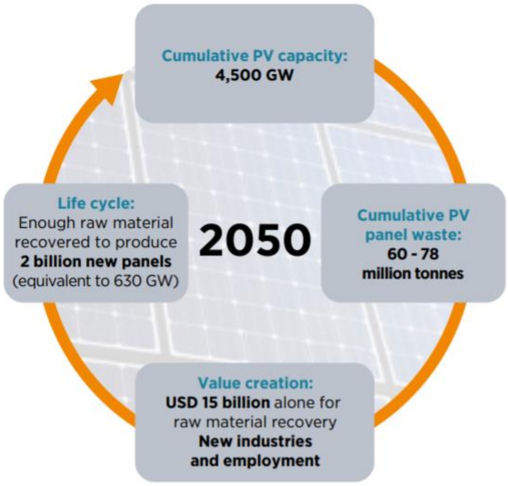


Figure 7.1. Potential value creation through PV end-of-life management to 2050 ([1], 2017)

7.4. Visual impact

Solar panels do have an effect on visual impact. Normally they can be placed on the rooftop or isolated location. Nevertheless, in this particular application they will change the aspect of the playground of the school.

8. Economic study

8.1. Budget

For this part, an estimation for the cost of the installation has been done. There are some costs that hasn't been considered because they are not included in the scope of the project.

Materials	Unit cost	Units	Subtotal
Solar modules			
JAP71S01-SC-330	155,79 €	40	6.231,60 €
Inverter			
SB6.0-1AV-41	1.449,59 €	2	2.899,18 €
DC connections			
2,5mm^2 XLPE cable	2,10 €	120	252,00 €
AC connections			
16mm^2 XLPE cable	3,40 €	20	68,00 €
Protections			
Fuses	3,03 €	8	24,24 €
Surge protector	53,51 €	4	214,04 €
Magnetothermal	94,63 €	1	94,63 €
Differential switch	107,26 €	1	107,26 €
Disconnector	42,99 €	1	42,99 €
SUBTOTAL			**9.933,94 €**
Engineering			
Development	45,00 €	100	4.500,00 €
Drafting of documents	30,00 €	80	2.400,00 €
TOTAL*			**16.833,94 €**

*IVA included

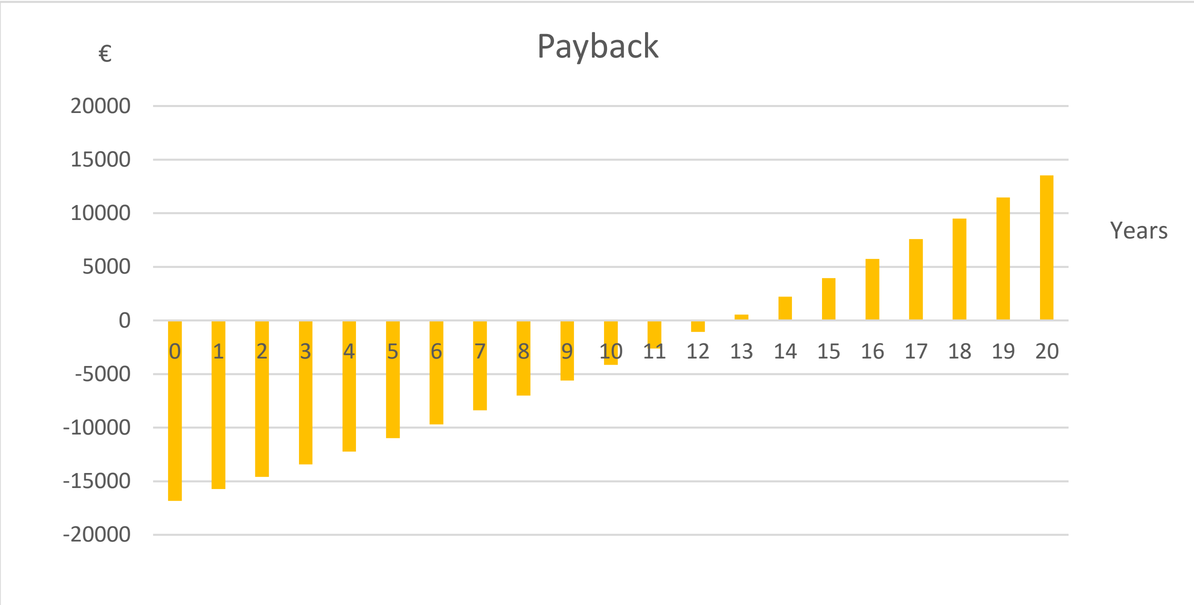
Table 8.1. Budget for the PV installation at Petit Lys

8.2. Analysis of the investment

Although the objective of this investment is not to obtain an economic profit, it is important to know when will the investment be recovered because the school needs to decide if it is viable to do the project.

As in the pre study made in the point 5.4.4, the cost of the electricity used is 0,125997€/kWh. Also, as mentioned before it would be ideal to have the hourly consumption for the whole year in order to have a more accurate calculation for the savings; but, for the moment, all the values are obtained with the consumptions available.

Considering the budget shown in the previous point and an incrementation of the 4% for the IPC of the electricity, the payback for the project is shown in the following graph:



Graph 8.1. Payback for the installation of 40 panels in Petit Lys

The investment is recovered after the 12th year. This value probably won't be useful for a business, usually the payback desired for a PV installation is less than 10 years. Although this value is not far from 10 years and again, the objective of this project isn't to meet the expectations of a business project. Therefore, with these values it is the choice of the school whether to make the investment or not.

Conclusions

Once the project is finished, an overview can be done obtaining some conclusions. The first thing that we can notice in the early phase of the project is that the available space in Petit Lys is better than the one at Escola Lys. At first, it could be like this is a problem because the consumption in Petit Lys is much lower than in the other school. However, since the collective consumption can be implemented, this fact won't imply a problem for the project.

Despite this, the shadows of the near buildings do imply an important issue. As we have seen in the previous points, the losses for shadows in Petit Lys are smaller than in Escola Lys, but they are still a big factor to take into account. These losses also translate in a longer period for the payback of the installation.

As it has already been mentioned during the thesis, this project is involved in an Environmental Commission and is thought to be complemented. Therefore, it is important to describe future consideration and variations that might be studied. In the first place, it could be interesting to study alternatives for the location of the panels, such as implementing them in the wall. This was an idea that came up whilst doing this project, however due to the lack of time it couldn't be considered. On the other side, if the installation proposed is kept, the study for the structure must be implemented. Again, the lack of time has been a crucial factor for not developing this part but also the lack of information. Since it is not the common structure, the photovoltaic pergolas are usually done under a project demand.

Also, for the future evaluation of the project it would be interesting to obtained the hourly consumptions for a whole year. This would give a much more exact study of the viability of the project.

Finally, it must be said that the implementation of PV panels would reduce drastically the emissions of CO_2 compared to conventional resources. This is an important factor to consider since the aim of the school is to become "greener".

Acknowledgement

In the first place, I would like to thank Oriol for the opportunity of participating in this project and of course, for all the support given during the evolution of this thesis.

Also, a special appreciation to Escola Lys for allowing me to see the installations of the school and provide as many information as it was possible, which made the project more accurate. I would also like to outline the emphasis that this school is giving on environmental projects that help building a better society and educate children.

Finally, I would like to thank my family, for having enough patience and giving me support when I the things were turning complicated. And of course, a big thank you for all my university classmates, not only for standing by my side during this project but for all the four years and a half, I am pretty sure that I wouldn’t be where I am right now if it wasn’t for their help at the right moments.

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